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ABSTRACT

The eight papers presented at the conference stress the importance of self-produced locomotion for the normal development of cognitive processes, particularly spatial understanding. Papers have the following titles and authors: "Childhood Motor Impairments: Clinical Overview and Scope of the Problem" (Ross Hays); "Locomotion and Psychological Development in Infancy" (Joseph Campos and Bennett Bertenthal); "Visual-Vestibular Integration in Early Development" (Bennett Bertenthal and Dina Bai); "Spatial Understanding in Infants with Motor Handicaps" (Robert Telzrow et al.); "Predictors of Successful Powered Mobility Control" (Geb Verburg); "Pediatric Powered Mobility: Service Delivery and Associated Research" (Ed Snell and Lynn Balfour); "Powered Mobility for Severely Physically Disabled Children: Evaluation and Provision Practices" (Elaine Trefler and Susan Taylor); and "Choosing a Powered Mobility Base for Pediatric Clients" (C. Kerry Jones). (DB)

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Childhood Powered Mobility:
Developmental, Technical and Clinical Perspectives

Proceedings of
the RESNA First
Northwest Regional Conference

March 6, 1987
Seattle, Washington

Kenneth M. Jaffe, M.D.
Editor

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CHILDHOOD POWERED MOBILITY: DEVELOPMENTAL, TECHNICAL AND CLINICAL PERSPECTIVES

PROCEEDINGS OF THE RESNA FIRST NORTHWEST REGIONAL CONFERENCE

Co-sponsored by
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School of Medicine

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CHILDHOOD POWERED MOBILITY: DEVELOPMENTAL, TECHNICAL AND CLINICAL PERSPECTIVES

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FOREWORD

Wheelchair toddlers, even powered ones, demonstrate our changing perspective on treatment of children with physical disabilities. Prescription of mobility devices is not new, but the commitment to providing functional, efficient mobility from earliest childhood is a considerable departure from former practice. Since the introduction of electric wheelchairs for adults, younger and younger disabled persons have achieved independence and improved quality of life with powered mobility. More recently, experiments show even toddler-age children can learn to drive skillfully within a short period of time.

Able-bodied toddlers move in constant exploration of their surroundings and, by three, expand their territory from home to yard to neighborhood. Locomotion which develops rapidly during the first two years of life is a primary vehicle for learning, socialization, and healthy growth of a sense of independence and competence. Our current view of child development emphasizes this interrelationship of social, emotional, intellectual and motor development and stresses that early experiences influence subsequent behavior. Research suggests that inability to be freely mobile in the formative years of early childhood has diffuse and long-lasting effects, particularly on the development of curiosity and initiative. In the absence of ambulation after the age of one year, it is essential to provide a substitute means of effective, self-controlled mobility for children. The aim is to promote their overall development.

This topic was the subject of a conference held in Seattle, Washington on March 6, 1987, sponsored by RESNA (Association for the Advancement of Rehabilitation Technology), Children's Hospital and Medical Center and the Departments of Rehabilitation Medicine of the University of Washington School of Medicine and at Children's Hospital and Medical Center. The purpose of the conference was to assemble some of the leading researchers and clinicians in rehabilitation medicine and psychology to provide a forum for presentation and discussion of their related work. Experienced educators, therapists, and policy-makers were also invited to discuss the implications of the data presented and to explore the critical questions for future research. This book contains the papers that were presented and provides a resource for persons interested in the possibilities of powered mobility for children of all ages.

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PREFACE

The symposium at which the following papers were originally presented was a multidisciplinary assembly of psychologists, educators, engineers, therapists and physicians who explored the developmental, clinical, and technological issues that are related to independent mobility for normal and disabled children. Hays sets the stage by reviewing the spectrum of clinical conditions for which the forward-thinking clinician is prescribing powered mobility devices. Through introducing the concept of cognitive-motor mismatch, he challenges many of the traditional yet unsubstantiated practices to which many,including third-party payers and other funding sources, tenaciously cling.

The significance of self-produced locomotion has received much attention in the field of developmental psychology. This body of knowledge, however, remains distant from those of us who as clinicians are responsible for managing the care of motor-impaired children. Campos provides an authoritative and scholarly review of the consequences of the development of independent mobility on cognitive processes, particularly spatial understanding.

Bertenthal's paper explores, through his own experiments, the mechanisms by which infants perceive self-motion and how such motion results in changes of sensory organization. Telzrow demonstrates the functional relation between spatial search performance and locomotion in children with spina bifida, providing further evidence for the key role that locomotion plays as an organizer of spatial cognition. The preliminary data presented by Verburg attempts to identify those variables which can help the clinical team reliably predict which disabled children will be able to safely drive a powered mobility device.

The exemplary service delivery model for powered mobility devices at the Hugh MacMillan Medical Center is reviewed by Snell. He thoroughly addresses assessment, training, and issues about wheelchair and interface selection, reflecting the collective experience of a leading-edge center. Jones' soup-to-nuts guide on choosing a powered mobility base, clearly and comprehensively outlines those factors that must be carefully considered by the clinical team, family, and client.

Motor activity and independent exploration enable children to know the world in which they live. Cognitive, emotional and social development are intimately tied to independent mobility. Young motor-impaired children can have developmental experiences similar to their able-bodied peers through the timely prescription and application of powered mobility devices.

Kenneth M. Jaffe, M.D.

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Special thanks are extended to the Planning Committee of RESNA'S First Northwest Regional Conference, *Childhood Powered Mobility: Developmental, Technical and Clinical Perspectives.* Through the creative efforts of Charlene Butler, Elizabeth Director, Gerald Warren and Lynn Wolf, the Conference was successfully conceived, organized and executed.

Kenneth M. Jaffe, M.D.
Editor

CHILDHOOD MOTOR IMPAIRMENTS: CLINICAL OVERVIEW AND SCOPE OF THE PROBLEM

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ABSTRACT

The population of children requiring power mobility is relatively new and undefined. These children represent a mismatch between relatively good cognitive potential and severe motor disability. They can be divided into a number of diagnostic categories, of which the best understood is cerebral palsy. In addition to this, there are inherited neuromuscular diseases which include Duchenne muscular dystrophy, Becker muscular dystrophy, spinal muscular atrophy, and occasionally rarer inherited neuromuscular diseases. Acquired etiologies include traumatic brain injury, spinal cord injury, juvenile rheumatoid arthritis, and rarely acquired neurologic sequelae of infectious disease. Congenital defects include myelomeningocele, limb deficiency, arthrogryposis and osteogenesis imperfecta. Each of these diagnoses has a different set of implications for the functional mobility of the child. For some, power mobility will aid in the acquisition of developmental skills; for others, the issue is adaptation to disability. The cost of mobility is discussed in terms of energy expenditure for ambulation and of financial resources required for power mobility. Implications for evaluation and patient selection and the future of this population are explored.

The concept of children requiring power mobility is a relatively new and undefined entity in medicine. These children represent a diverse spectrum of disorders and will use a variety of medical interventions. It is the purpose of this paper to attempt to bring some structure to the description of this important population.

There is no data available at this time regarding the actual numbers of children using power mobility. A recent poll of suburban public school districts in Washington State documented ten power mobility users in a total enrollment of 15,438 children. This would correspond to 6.5 per 10,000 school age children. In a review of prescribing patterns in the Pediatric Rehabilitation Clinic at Children's Hospital and Medical Center in Seattle, approximately 5.4% of all clinic visits were involved with the prescription of power mobility. In the same clinic, with a relatively large population of inherited neuromuscular disorders and closed head injury, approximately 17% of the patients use power mobility.

To better understand the issues involved in the prescription of power mobility, it is useful to consider the concept of the "cognitive motor mismatch." The wide range of childhood disability can be described as a continuum. One end is represented by the normal child, in whom we expect an orderly acquisition of cognitive and motor skills along a standard chronological sequence. At the opposite end of the continuum is the severely disabled child who suffers from a combination of profound intellectual and motor impairment. For children at these extreme ends of the continuum, there would be no indication for the prescription of power mobility. The child who will require a power wheelchair has a mismatch of cognitive and motor skills, which may be described as adequate cognitive ability to manage or incorporate mobility into development without the minimum motor skills to achieve efficient independent mobility. This concept of the cognitive motor mismatch is useful in defining which populations of children and which subgroups among the different diagnostic categories will benefit from the prescription of power mobility.

Perhaps the best understood and most widely recognized diagnostic category for which power mobility is prescribed is cerebral palsy. The 1978 Collaborative Perinatal Project estimated a prevalence of 5.2/1,000 children at age 7 years Nelson & Ellenberg, 1978). The American Academy for Cerebral Palsy and Developmental Medicine describes this disorder as a nonprogressive condition characterized by a disturbance of motor ability resulting from impairment of function of intracranial central nervous system structures that has occurred during the growth and development phase of brain maturation (Bax, 1964). The group of patients fitting this criteria is necessarily broad. Several subgroups, such as the mild spastic hemiplegic and the mild spastic diplegic, will fall toward the normal end of the cognitive motor continuum. Similarly, the hypotonic child with microcephaly and profound mental retardation would fall toward the severely disabled end of the continuum. Those patients who would be more likely to make use of power mobility in the middle of the mismatch area would have diagnoses including the spastic quadriplegic form of cerebral palsy, the more severely involved spastic diplegic, and the athetoid form of cerebral palsy. The patient with ataxic cerebral palsy may have inefficient independent mobility and thus eventually require a power wheelchair.

The most rapidly progressive and best studied of the inherited neuromuscular disorders is Duchenne muscular dystrophy. This disease has an incidence of two to three per 10,000 male births (Brooke, 1986). It is marked by an inexorable progression of muscular weakness leading to loss of ambulation at the end of the first decade. A large multiclinic study reported by Brooke reports that the average age of cessation of independent ambulation is 12.3 +/- 1.7 years (Brooke et al., 1983). Prescription of power mobility patterns for this group of patients has changed within the last generation. Previously, a manual wheelchair was prescribed at the time of loss of ambulation and was later replaced by a power wheelchair. It has now been found that prescription of power mobility is a reasonable first choice and is often prescribed at the time when loss of ambulation is imminent. Becker muscular dystrophy, the less common and possibly allelic form of x-linked progressive muscular weakness, also requires power mobility. It is uncommon for patients affected with Becker muscular dystrophy to lose ambulation before 16 years of age, but nearly all will require power mobility by the third decade (Brooke, 1986). The prevalence of spinal muscular atrophy (SMA) in the general population has been reported to be between one in 15,000 and one in 25,000. Spinal muscular atrophy has been variously described as a broad spectrum of a single disease or a collection of several different diseases (Eng et al., 1984). It is most useful to think of the disease as three separate types. Type I, frequently referred to as Werdnig-Hoffman disease, represents 27% of the total group. These children are frequently diagnosed at birth, always within the first three months of life, and have progressive lower motor neuron degeneration and weakness with life span usually less than three years. At the other end of the spectrum is Kugelberg-Weilander disease or SMA type III. This form comprises 24% of the total group and usually has an onset between ages five and 15. The disease progresses requiring power mobility at adolescence and life span frequently extends to middle age. Between these two groups, 49% of those affected children will fall into the intermediate or spinal muscular atrophy type II category. This is the most heterogeneous type. Children affected with the intermediate form of spinal muscular atrophy usually experience onset of weakness at less than one year of age. They may or may not walk for a brief period of time. All of these children will require power mobility. The life span of children with SMA type II is quite variable and has been reported from five years to middle age. There are other, rarer inherited neuromuscular diseases for which power mobility has been used infrequently. These include Freiderich's ataxia, myotonic dystrophy, and a number of the rarer myopathies and neuropathies.

Juvenile rheumatoid arthritis has an incidence of approximately 1.1 cases per 1,000 children, and affects 66,000 children in the United States. It is now accepted that there are at least seven different patterns of involvement with some overlap in each (Wedgwood & Schaller, 1977). Children who are most likely to have severe progressive joint deformity and require power mobility are those who have the combination of systemic disease and polyarticular joint involvement. Similarly, in the polyarticular category, the rheumatoid factor positive subgroup, mostly females, will also have progressive severe joint deformity and may be candidates for power mobility.

Traumatic brain injury associated with closed head injury has an incidence estimated to be between 180 and 295 per 100,000 children per year. The incidence is higher for boys than for girls and increases steadily from age five to a peak at age 15 years of age (Rivara & Mueller, 1986). The natural history of recovery from traumatic brain injury suggests that the potential for motor recovery is quite good. The subgroup requiring power mobility usually includes those who have had severe traumatic brain injury and endured prolonged periods of coma or those who have a combination of traumatic brain injury with additional anoxia or multiple injuries (Jaffe & Hays, 1986). Spinal cord injury affects 11,000 people per year in the United States, 10% of whom are under 15 years of age. Children have a greater risk of cervical spine injury than adults. Approximately 60% of these will be the result of motor vehicle accidents, followed by trauma from sporting accidents, falls, gunshot wounds, and birth trauma (Perrin, 1982). Generally in adults and older children, those with spinal cord injury below the C7 level will be independent without power mobility. Those patients requiring power wheelchairs usually have higher cervical spinal cord lesions. Occasionally the developing young child with lower cervical spinal cord injury will require power mobility. Rarely, the sequelae of central and peripheral nervous system infection such as meningoencephalitis, transverse myelitis or Guillain-Barre syndrome (Evans, 1986) will necessitate the prescription of power mobility.

Myelomeningocele occurs in approximately 0.9 per 1,000 live births in the United States (Shurtleff et al., 1986). These children will have significant motor deficits in the lower extremities; however, the great majority of them will be independent in either ambulation or propulsion of a manual wheelchair. Rarely, the child who has significant complications of hydrocephalus and/or central nervous system injury will demonstrate significant upper extremity involvement and will require a power wheelchair. It has been advocated in some centers that although children with spina bifida will usually be able to maintain independent mobility with a manual wheelchair, a power wheelchair during the early period of development may provide a more appropriate developmental experience (Shurtleff, 1986).

It is estimated that there are at least 4,000 children in the United States with limb deficiency, either congenital or acquired. It is also estimated that this population increases by approximately 17% per year. The most frequently encountered deficiency is the below-elbow upper extremity form which requires no assisted mobility. Children who suffer three extremity deficiencies, including both lowers, represent 1.5% of the total population. Children with absence of all four extremities make up another 4.4% (Hays et al., 1987). It is this small subgroup of the limb deficiency population which will benefit from the prescription of power mobility.

Arthrogryposis or the syndrome of multiple congenital contractures has been estimated to occur in approximately 500 to 1,000 births per year in the

United States (Swinyard, 1982). Approximately 20% of these will involve the lower extremities and a smaller percentage will have lower extremities fixed in flexion. Seventy percent will have involvement of all four limbs (Hageman & Willemse, 1983). The child with flexion deformities at the lower extremities or four extremity involvement will be more likely to require power mobility (Hahn, 1985). Osteogenesis imperfecta affects one per 30,000 births. There are many different methods for categorizing the disorder. Very simply, osteogenesis imperfecta type I is an autosomal dominant disorder with fractures in childhood which are disabling to a various degree. Type II, or the "congenita" autosomal recessive type, is associated with severe involvement, intrauterine fractures, and death during infancy or the perinatal period. The type III recessive form is characterized by frequent fractures and bony deformity in early childhood. Type IV is a rare autosomal dominant type with variable bony involvement (Hageman & Willemse, 1983). Type II falls at the severely disabled end of the continuum and would not require assisted mobility. Type I is often at the more normal end of the spectrum and again requires no assistance. It is more likely that type III's and type IV's will make use of the power wheelchair (Binder et al., 1984).

It is useful to place these diagnostic categories within a functional frame of reference. The implications for mobility and its integration into the child's overall concept of disability can be better understood by assessing the functional impact of power mobility in each group. For these purposes these children can be divided into four functional subgroups. The first group is comprised of children who will never ambulate. Representative diagnoses include severe cerebral palsy with spastic quadriplegia or athetosis, spinal muscular atrophy Types I and II, limb deficiency with three or four limb involvement and neonatal spinal cord injury. These children will have no opportunity for independent mobility outside of the prescription of the power wheelchair. For these patients, independent control of mobility and its developmental consequences are completely dependent on the provision of power mobility. The second group includes the child with inefficient mobility: the child who ambulates or uses a manual wheelchair but is unable to do so at a reasonable rate of speed or with acceptable endurance. This group of children includes the cerebral palsy patient with milder forms of quadriplegia and athetosis, the child with ataxia and the spastic diplegic child with significant upper extremity overflow tone. It would also include the marginal wheelchair user with C6 to 7 level spinal cord injury and the myelomeningocele patient with upper extremity involvement. For these children, the power wheelchair provides the opportunity to simulate normal childhood by providing an efficient means of mobility above that which they are capable of producing themselves. A third group includes the child with loss of independent mobility. All victims of trauma, including traumatic brain injury and cervical spinal cord injury, will belong to this group as well as those children with progressive neuromuscular disorders. For this group, the developmental implications may be less critical, as the timing of loss of ambulation is frequently beyond the early period of development. The more significant functional issue in this category is the acceptance of assisted mobility as an adaptation to acquired disability. The last functional category includes the child who temporarily requires assisted mobility. This is certainly the smallest group. Examples would include children with arthrogryposis who subsequently have surgical correction of the lower extremities and rarely the osteogenesis imperfecta child who requires assisted mobility for protection during early childhood but can progress to independent mobility with age. The functional considerations in this group are both developmental and practical.

After a clear examination of the existing patient population, it is reasonable to look toward the future. Questions which will become increasingly important include the quantification of the cost of mobility. This cost can be described in two very different realms. For the disabled child, independent mobility, either in ambulation or in propulsion of a manual wheelchair, entails a cost which can be measured in terms of energy expenditure. For the medical community and society at large, a very different cost for power mobility can be measured in terms of health care dollars.

The cost of independent mobility in children is a fruitful area for further investigation. Since the 1950's, the combination of improved technology for measurement of energy expenditure and interest on the part of clinicians dealing with the handicapped population have coalesced to create a reasonable body of information regarding energy expenditure in health and disease. The great majority of this work has been done to study the adult population (Fisher & Gullickson, 1978). There is much less information available regarding children and even less available in the area of wheelchair ergometrics in the pediatric population. Energy cost studies are valuable methods of determining the physiologic penalties imposed by abnormal gait or inefficient manual wheelchair use. The most useful measurement is indirect calorimetry, which is often expressed in terms of oxygen consumption. It is well documented that the normal adult walks at approximately 83 meters/minute and expends 0.063 kcal/kg/min. (Fisher & Gullickson, 1978). Both energy costs in terms of oxygen consumed per kg/meter and the rate of energy expenditure, oxygen consumed per kg/min, have been shown by Waters and others to have a linear correlation with age (Waters et al., 1983). Children under age six expend approximately 15.3 ml O_2/kg/min, while adults will expend only 11.9. The efficiency of ambulation is also well correlated with age. A two-year-old will average an ambulation speed of 46/meters/min. By age 12 years this has increased to 81 meters/min; the accepted adult values are 83 meters/min. These parameters have also been documented for the cerebral palsy population by Campbell and Ball (1978). The normal 10-year-old child will expend approximately 15.3 ml O_2/kg/min but the age-matched child with cerebral palsy will expend approximately 22.9 ml O_2/kg/min. The ambulation speed of a 12-year-old of 81 meters/min has been compared with a group of 10-year-olds with cerebral palsy. These disabled ambulatory patients walk at 43 meters/min, nearly half the normal velocity. When subjected to careful analysis, the significance of the difference in cerebral palsy children versus matched able-bodied children has a statistical significance in the $p<0.05$ range (Campbell & Ball, 1978).

In their excellent review of the literature regarding energy costs of ambulation in health and disability, Fisher and Guillickson (1978) were able to summarize the research available to date and postulate a number of principles. These include the observation that normal and disabled persons naturally attempt to walk at a speed which is most efficient in terms of energy expenditure per minute. Disabled persons decrease their speed of walking so that energy expenditure approaches the normal range. Examples of this include the fact that a hemiplegic person walks 46% slower and expends 16% less kcal/min and 63% more kcal/meter than normal controls. An average above-knee amputee will walk 43% slower, expending 5% less kcal/min and 89% more kcal/meter than a matched control. Any ambulatory aid that increases effort is likely to be abandoned and the closer the gait pattern is to the normal the less energy will be expended.

Since 1952 there has been interest in the applications of indirect calorimetry to the wheelchair bound population. Wheelchair ergometrics have been studied; however, there are significant difficulties in applying this data to our population. Dreisinger and Londeree (1982) comment that the available data related to wheelchair ergometry is limited primarily due to a lack of instrumentation which was able to provide reliable physiological data in the wheelchair population before 1982. There are other difficulties, including the lack of correlation between free wheeling wheelchair mobility and the more standardized arm powered ergometry. Technical variables such as translational inertia are also difficult to control. Most important for this population, there is a paucity of data regarding wheelchair energy expenditure in children and especially in children who have upper extremity involvement. This continues to be a fruitful area for further scientific investigation (Evans & Tew, 1981; Richerson & Richerson, 1981). An interesting model for practical applications of energy expenditure study in the disabled pediatric population was proposed by Rose, Medeiros and Parker in 1985. This group sought to provide an easily measurable index of energy costs in the cerebral palsy population. The intention was to efficiently and economically measure energy expenditure with different ambulatory aids to more objectively determine the most appropriate prescription of adaptive equipment. Their study was based on the fact that for those children with no handicaps or only lower extremity handicaps, oxygen consumption and heart rate were linearly correlated. Using this information, they were able to develop an energy cost index defined as the heart rate per minute divided by ambulatory velocity in meters per minute. This energy cost index was easily obtained without the use of cumbersome or expensive indirect calorimetry methodology. Children were used as their own controls and evaluated using quad canes and walkers. The energy cost index was determined under each testing situation. Using this objective measurement, recommendations were made about the application of ambulatory aids. The conclusion was that there is a possibility of a more objective means of evaluation using energy expenditure measurement to improve the ambulation and mobility of disabled children. The future of scientific investigation in this area will likely be most fruitful if the technology can be mobilized to provide good standards for wheelchair ergometry in disabled children. A reasonable goal would be to develop an objective threshold above which inefficiency in manual wheelchairs is no longer acceptable. The energy cost index as described by Rose is a useful model for this type of threshold measurement. Further investigation will determine whether or not such an objective measurement can be devised for the wheelchair population. Improved measurement tools may allow prescribers dealing with these children to objectify the need for power mobility and thus broaden its use.

In an era of cost containment in medicine, it is important for health care professionals to consider the financial expenditure required for power mobility. A review of the wheelchair prescriptions at Children's Hospital and Medical Center in Seattle indicates that there has been an inflation in the cost of the average power wheelchair over the last three years. Records reveal that the average cost of a power wheelchair in 1984 was $5,491. In 1985, this cost had increased to $5,918, and in 1986 the average price had risen to $7,299. There also appears to be some correlation between different diagnoses and the cost of wheelchairs.

Wheelchairs provided to children with muscular dystrophy averaged $6,491 in 1986; whereas those provided to children with cerebral palsy averaged $8,151. This difference based on diagnosis is easily explainable on the basis of increased high technology adaptations required for the control of the wheelchair by the cerebral palsy population. The increase in price over years is also commensurate with the inflation in health care expenditures in general. It may also represent a combination of increases associated with more elaborate and expensive technology and decreases reflecting more competition in the marketplace.

The population of children for whom power mobility is an option will continue to grow. It is the responsibility of the health care community to provide realistic developmental and physiological criteria for patient selection. At the present time, patient selection or the prediction of success with power mobility is not standardized. The process is often imprecise and occasionally arbitrary. Successful prediction of the use of power mobility appears to be dependent upon the experience of the evaluator. There is also concern that financial considerations will play an increasingly large role in the allocation of these resources.

In the past generation of medical care, chronological age was often used as the sole criterion for prescription for power mobility. In most centers this has been abandoned. It is of some concern, however, that many third party payers are still unwilling to consider power mobility for the preschool age child. There has been tremendous development in the microswitch technology and computer assisted control of power mobility within the last decade. With this very sophisticated equipment providing an interface between the patient and the machine, there are very few contraindications to prescription of power mobility based on the child's limited motor control. Cognitive ability of the patient is a much more meaningful consideration. There are at this time no objective standards to determine the cognitive readiness for power mobility. It is likely that in the near future linkages between several areas of development, especially the area of receptive language which is much less affected by motor impairment, will be used in a more standardized fashion to develop the minimal cognitive criteria required for the use of power mobility. Development of an energy efficiency threshold measurement will provide a better standard for determination of energy cost in wheelchair mobility. Financial considerations will continue to exist. It will benefit the patient population at large and the medical community if a concerted effort can be made to educate third party payers regarding the developmental advantages and true medical necessity of power mobility for young children.

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LOCOMOTION AND PSYCHOLOGICAL DEVELOPMENT IN INFANCY

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Importance of self-produced locomotion

There may be no phenomenon in developmental psychology which has been given more significance by so many theorists, yet been the subject of so little empirical research, as the development of self-produced locomotion. This motoric skill has been linked theoretically to the development of spatial cognition, the use of emotional information from others, a new level of self-awareness, a shift in the development of attachment, the growth of brain structures, and the emergence of new capacities to cope with environmental stressors. Moreover, clinicians and therapists have often suspected that deficits in locomotion are linked to deficits in specific cognitive domains, while parents intuitively react to the onset of locomotion as a crucial milestone in their infant's growth toward maturity. Yet, despite a wealth of psychological and pediatric data on norms of self-produced movement, we know preciously little about the correlates and consequences of its development.

Theorists who have postulated a role of central significance for self-produced locomotion include psychoanalysts, cognitive theorists, neurophysiologists, and perceptionists. For instance, Mahler explicitly predicts that two of the major subphases of ego development – the early "practicing" phase and the "practicing period proper" – are ushered in by the development of crawling and upright locomotion, respectively (Mahler et al., 1975). She, like Spitz, also predicted profound changes in mood, feelings of self-efficacy, patterns of attachment, and new challenges to the caregiver-child relationship resulting from the development of locomotor capacities – in particular, the transition to walking that takes place between 11 and 14 months of age (Spitz, 1965). Piaget (1951, 1954) makes self-produced movement a crucial building block of knowledge. He believes that the intercoordination of vision and audition with movement (including locomotion) lays the basis for the child's understanding of space, objects, causality, and the self. Gibson (1979), despite disagreeing with Piaget on the origins of knowledge, likewise stresses the importance of self-produced movement as a primary mechanism for the detection of information in the visual and auditory world. Neurophysiologists, such as Bernstein (1967) and von Holst and Mittelstaedt (1950), have proposed formal models of how the brain requires information about self-produced movement in order to make sense of incoming sensory information. Finally, Held and Hein (1963; Hein, 1972) have empirically documented the importance of active, self-produced movement for normal sensory-motor development in young animals, and for perceptual adaptation in adults.

Given this extraordinarily diverse theoretical agreement about the significance of locomotion, and given the central importance that virtually all of these theories play in contemporary developmental psychology, it is mystifying that there is so little empirical research on the psychological processes affected by the development of self-produced movement. We trace the neglect primarily to three factors in the zeitgeist: the misinterpretation of influential early studies on motor development, the domination of psychology by linear developmental models such as Stimulus-Response theory, and the absence of methods to investigate the theoretically most significant issues. We will elaborate on each of these three factors briefly, propose that they do not apply to contemporary investigations of self-produced movement, and then proceed to describe a series of investigations from our own and other laboratories which demonstrate the powerful and widespread impact of the acquisition of self-produced locomotion for emotional and spatial cognitive development.

Neglect of self-produced locomotion as an organizer of early development.

The misinterpretation of early studies on motor development: Child psychologists often equate the significance of a phenomenon with its success in predicting later outcomes, relegating to secondary importance variables that lack predictive ability. The study of motoric activity fell victim to this bias. In the 1930s, much hope was placed in the possibility that advanced motoric development in infancy and early childhood forecast advanced intellectual development in later childhood and adulthood. The research, however, failed to support such relationships (Kopp, 1979). Moreover, attempts to accelerate motor development to create permanent motor precocity in infants also failed (McGraw, 1935). Given that most of the remaining research on motor development was merely normative and descriptive in scope, the developmentalists of the 1930s prematurely concluded that motoric developments were likely irrelevant to or uncorrelated with factors of psychological importance.

In retrospect, it is apparent that this line of research failed because the questions posed (a) were much too broad to test rigorously, (b) did not take into account domain specificity in cognitive development, (c) did not tap the processes which were most likely to be influenced by motoric skills, and (d) focused too much on motor abilities as predictors of future outcomes. Most importantly, early research did not investigate periods of rapid developmental changes in order to determine the role of motor abilities as determinants of new skills responsible for inducing developmental changes that would not otherwise occur, or for accelerating changes that other developmental processes were less likely to bring about.

Dominance first of environmentalism, then nativism: A second reason for the neglect of the role of self-produced locomotion as an organizer of psychological changes was the domination of developmental psychology by two metatheoretical views, neither of which adequately considered the importance of the experiences generated by the organism's voluntary activity as a mechanism for psychological growth. Rather, these views construed development as under the control of either the passive registration and storage of stimulation imposed from outside the organism (empiricism), or the unfolding of a genetic blueprint (maturationism or predetermined epigenesis) (Gottlieg, 1983).

These views led to beliefs that either the infant is passive and at the mercy of its environment, or that the infant's brain, although "active and striving," imposes its intrinsic organization on experiential input through exclusively "hardwired" processes. Neither position adequately conceptualized how the organism can set the stage for its own development by virtue of the environmental changes that are brought about through self-produced movements in space. When, for example, nativists discussed the functions of certain developmental changes, the functions dealt with biological adaptations which presumably took place eons ago in the so-called "environment of evolutionary adaptedness." However, the contemporaneous functions served by developmental changes in locomotion on social understanding, spatial cognition, and emotional development were not considered.

Only recently, as the field of developmental psychology has more readily adopted an interactionist perspective, and as system's approaches to development have proliferated, have the issues of the role of each new developmental acquisition on the functioning of the whole organism been addressed more frequently (Greenough et al., 1987; Schneirla, 1957). Such metatheoretical changes have created a more fertile ground for considering whether organismic changes such as the development of locomotion may be responsible for other developmental transitions.

Absence of research strategies: The last factor that contributed to the neglect of self-produced locomotion as an organizer of psychological development was methodological. Until recently, few research strategies existed that were appropriate to issues concerning the role of locomotion as an organizer of psychological development. (In this chapter, we use the term "organizer" to mean a general process that subsumes Gottlieb's (1983) notions of induction and facilitation, and also refers to the direct or indirect mediation of psychological changes.)

Historically, most research on locomotion was limited to correlational studies involving locomotor development and a simultaneous or subsequent psychological change, or to tests of hypotheses with animal models. Both strategies are equally unsatisfactory to developmental psychologists: Correlational approaches reveal little about the processes of developmental change, and animal studies are frequently species-bound, revealing few processes generalizable to the human.

Clearly, more convincing approaches needed to be developed to determine whether self-produced locomotion influences psychological development. Training studies meet such a criterion, because they permit the presumptive antecedents of a phenomenon to be manipulated in advance of their ordinary appearance, and the effects of such training on later development are then assessed (Harris, 1983). In addition to permitting one to infer some causal role, training studies have the further advantage of permitting us to draw broader generalizations than is otherwise possible, to the extent that such training methods often parallel methods used in animal studies of the effects of early experiences.

Although often implemented in clinical evaluations, such training studies are relatively rare in basic research on developmental processes in humans. However, it is the use of such training methods that has rejuvenated interest in the study of the consequences of self-produced locomotion. More specifically, it is possible to use "enrichment" paradigms (whereby experience not otherwise available to the subjects is experimentally provided), and "deprivation" paradigms (whereby the experience ordinarily available to the subject is experimentally prevented). Such training studies can then complement the more readily conducted age-held-constant studies (whereby one index of developmental change – age – is controlled, but other factors are allowed to differ in order to see the correlates and consequences of such factors) and lag designs (whereby one separately assesses the contributions of age and locomotor experience).

Paradigms to study the effects of self-produced locomotion: Let us begin by considering "enrichment paradigms" in the context of the study of the consequences of self-produced locomotion. Recent developments in the baby toy industry now make it possible "artificially" to provide crawling experience to pre-locomotor infants. Specifically, infants younger than crawling age (which begins at 7.1 months, on the average, according to Bayley Scale norms) can be given "walker" devices to provide them with experience with self-produced movement. This manipulation permits identification of the role of locomotor experience independent of other maturational factors correlated with the onset of crawling. Such an "experimental" manipulation encounters no ethical problems of experimentation if parents intended their infants to use these devices. Conversely, a "deprivation" paradigm involves determining the extent to which an impediment to self-produced locomotion retards the development of certain psychological processes. Infants with orthopedic, but no associated neurological, handicap represent an ideal group for evaluating whether any psychological impediments are produced by the absence of self-produced locomotion. Generally, orthopedically-handicapped infants, such as those born with a congenitally-dislocated hip, will have no confounding central nervous system impairment.

However, experience has taught us that it is not as easy to study infants with orthopedic handicaps as one would think. Although orthopedic problems in infancy are relatively common, the recent introduction of very light casts to correct clubfoot or congenital dislocation of the hips permits most orthopedically-handicapped infants to move about on their own at much earlier ages than heretofore expected, thereby short-circuiting to some extent the effects of the locomotor handicap. Nevertheless, the investigation of the consequences of an orthopedic handicap provides an important opportunity for studying the effects of deprivation of self-produced locomotion. Another strategy involves studying children with spina bifida or other neurologic anomalies. These infants provide useful information about deficits resulting from locomotor impediment to the extent that the degree of cerebral impairment can somehow be assessed and partialled out of their performance on the tests of psychological functioning that are believed to be linked to the locomotor activity.

Age-held-constant designs and lag designs that separately assess the role of age and locomotor experience are by far the most readily employable to study the correlates and consequences of the acquisition of self-produced movement. These paradigms do not require any special experimental intervention or the designation of any special populations for study. A cross-sectional age-held-constant design involves selecting infants of a given age (e.g., 7.5-month-olds), and dividing them into two groups on the basis of whether or not they are crawling. An essential component of an age-held-constant design is matching the infants in the two groups on significant variables such as age, sex, race, social class, etc. Differences between the two groups, then, are not likely to be due to the matched factors. Moreover, it is possible to evaluate quantitatively the relation between the amount of locomotor experience, on the one hand, and the magnitude of the outcome measure, on the other. By doing so, one can more completely describe the nature of the developmental process, i.e., whether there is a step-function relation, a steadily-increasing linear relation, or a spurt-plateau function between two variables such as the emergence of locomotion and a psychological outcome, e.g., a perceptual or cognitive process.

Findings from age-held-constant paradigms can be made more convincing by the addition of lag designs, which enable the experimenter to tease apart the age of onset of locomotion from the duration of experience locomoting. Such designs capitalize on the rather broad age range during which crawling can begin. (The Bayley Scales list the normal range of development of prone progression as extending from five to 11 months.) One can then assess whether it is the age of onset of locomotion, the duration of locomotor experience, or the interaction of these two factors that are associated with changes in the psychological outcome variable.

For instance, one can select a prelocomotor and a locomotor group at six, seven, eight, and nine months of age, and compare whether the differences between locomotor and prelocomotor groups are similar regardless of age, whether infants who started locomoting late show better performance than those locomoting early, or whether the effects of locomotor experience are the same, regardless of when the infant began to crawl. Moreover, the lag design permits testing whether similar durations of locomotor experience affect psychological outcomes in the same way regardless of the age of onset of locomotion. Lag designs can involve either longitudinal or cross-sectional comparisons. A longitudinal comparison involves testing the same infants repeatedly at different durations of locomotor experience. A cross-sectional comparison involves testing the infants only once, when they have had a predetermined amount of locomotor experience.

It is important to emphasize that age-held-constant designs by themselves cannot answer the question of whether experience with self-produced movement causes the psychological change. It is always possible that whatever factor brings about the emergence of self-produced locomotor capacities likewise determines the emergence of a time-related psychological skill. For this reason, the converging research operations of the enrichment and deprivation paradigms mentioned above are indispensable for a firmly-grounded conclusion. The advantage of conducting studies using an age-held-constant and lag designs as a first step in a research program is that they permit the investigator to determine whether the additional effort involved in the converging research operations is warranted by the initial results of these investigations.

Psychological domains affected by the development of self-produced movement: In our respective laboratories at the University of Illinois and the University of Virginia, and at the University of Washington in collaboration with Dr. Robert Telzrow, we are conducting a wide-ranging investigation into those psychological processes that are most likely to be influenced by the development of crawling, creeping, and upright locomotion. These processes include the development of fear of heights, changes in spatial search skills and spatial coding by the infant, and the appearance of new forms of emotional communication. In the remainder of this chapter, we focus on the first two outcomes, and leave for future presentations any discussion of the third.

The development of fear of heights

No phenomenon in developmental psychology better exemplifies the two polar-opposite approaches of nativism and empiricism than the phenomenon of fear of heights. With few exceptions, developmental psychology textbooks hold that wariness of heights is innate, a conclusion presumed to be supported by a variety of studies of animals and human infants on the visual cliff. Such an argument is typically buttressed by consideration of the great biological adaptive value of avoidance of heights, since falls can produce serious injury or even death for a young infant.

Alternatively, some have proposed that wariness of heights may be determined by very specific experiential factors, such as falls. Walk (1966), for instance, collected data showing that falling experiences can play a role in the acquisition of the wariness of heights (although he also noted that falls are not necessary for the development of depth perception). In point of fact, falls of a fear-provoking nature probably occur frequently in the everyday life of the young child, and the infant may be biologically prepared to associate heights with such falls. Both the nativist and empiricist positions are thus plausible.

It is our contention, however, that neither of these classic views on the development of fear of heights is accurate. The evidence is now clear that the emergence of wariness of heights, as assessed on the visual cliff, is not innate, but follows the acquisition of self-produced locomotion. Moreover, experiences with falls are not necessary for the development of wariness of heights.

One of the earliest indications that locomotion plays a central role in the emergence of wariness of heights comes from the classic and well-controlled research by Held and Hein (1963). In these experiments, kittens and their mothers were reared in complete darkness from birth until visual exposure began at eight to 12 weeks of the kittens' age. Visual experience took place in a special apparatus known as the kitten carousel that equated the visual experience received by each littermate. One of the kittens in each pair was allowed to move on its own within the carousel, while the other was moved passively, but in a manner perfectly yoked to the movement of the active kitten. The results of this study demonstrated that the actively-reared kittens showed avoidance of heights on a visual cliff, whereas the paired littermates did not. In short, the development of fear of heights was neither maturationally determined, nor the result of specific experiences with falls. Rather, it emerged as an outcome of experiences with active, self-produced movement.

These initial findings by Held and Hein have been replicated several times, but their implications for understanding human infant development are generally ignored because of the reluctance of developmentalists to accept findings that assume generalization from animals to humans (Hein et al., 1970). In addition, the dark-rearing procedure used by Held and Hein appeared to lack ecological validity, insofar as human infants are not visually deprived. In spite of these reservations, the principal finding appears equally valid for human infants: the emergence of wariness of heights follows the development of self-produced locomotion in the human infant just as it does with the visually-deprived kittens.

The first indication that wariness of heights is not innate in human infants came from interviews of mothers, who frequently reported a concern that their babies, in contrast to what they expected from textbooks, seemed to show little wariness of heights shortly after they started to crawl (Hein et al., 1970). Most mothers alluded to a stage after their infant began to crawl when the baby would go over the edge of a changing table, a sofa, the top of a staircase, or some other precipice. This finding was noted before, but explained away (Campos et al., 1978). However, our research using all four design paradigms described above to study the impact of self-produced locomotion–age-held-constant, "enrichment", "deprivation", and age/locomotor experience manipulations–provide converging evidence on the role of crawling experience as an organizer of fear of heights.

In one of the first experiments, we compared the visual cliff performance of prelocomotor and locomotor infants, using the age-held-constant design (age at testing was 7.3 months). Ordinarily, the test of human infants on the visual cliff involves placement of the child on a strip that divides the "deep" from the "shallow" side of the visual cliff, and asking the mother to call to her infant first from across the shallow side, and then from the deep, or the reverse. The dependent variable in this procedure, which we call the "visual cliff crossing test," is the latency shown by the infant to place all four limbs onto the glass surface that covers the deep or the shallow side, or, more demandingly, the tendency of the infant to cross the entire extent of the deep and the shallow side to reach the mother.

Because prelocomotor infants cannot be expected to cross to the mother, we developed an alternative procedure to test for wariness of heights. This procedure involves lowering the infant slowly from a height three feet above the glass surface of each side while simultaneously measuring the infant's heart rate. We call this procedure the "descent paradigm." Such a procedure, of course, does not depend on the infant's locomotor skills, and thus permits an unbiased assessment of differences in cardiac response to the deep and shallow sides of the cliff as a function of locomotor status. Because it is now reasonably well established that an infant's heart rate tends to decelerate in conditions of rapt attention, and to accelerate in conditions of wariness or fear, a shift from deceleration or no cardiac response to marked acceleration upon descent toward the deep side can be interpreted as a shift from no fear to fear of heights (Campos, 1976; Sroufe & Waters, 1977).

In this study, prelocomotor infants showed no significant changes in cardiac response as they were lowered either to the shallow or to the deep side of the cliff. By contrast, locomotor infants showed significant heart rate accelerations on the deep side, but no significant heart rate changes on the shallow. This interaction between side of the cliff and locomotor status suggested that wariness of heights may indeed be a function of experience locomoting, even when age is held constant at 7.3 months.

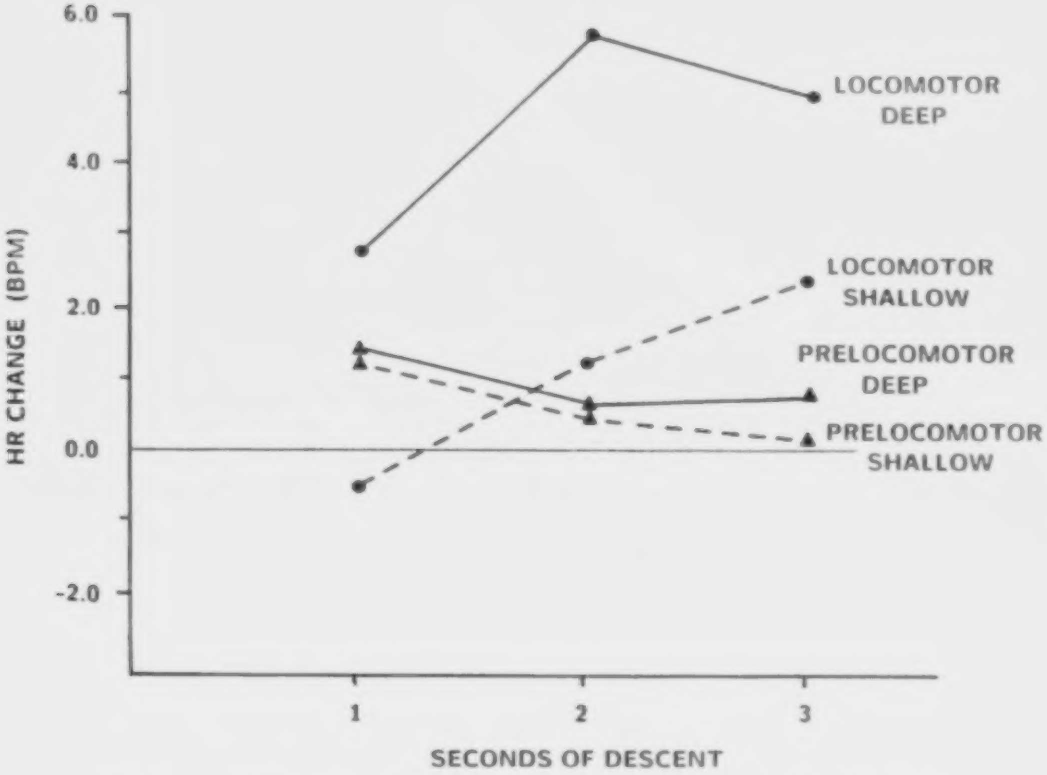

Fig 1. *Heart rate changes during descent toward the deep anc shallow sides of the visual cliff in 7.3-month-old infants as a function of whether the infants had crawling experience or not. Data show the second-by-second heart rate changes during descent toward each side of the cliff.*

The second study in this series involved the use of "walker" devices to determine whether wariness of heights was a function of experimentally-induced locomotor experience. In this study mothers were contacted well before their babies began to crawl, at which time, we determined whether they intended to provide the infant with a walker. If they did, we provided them with a walker for their infant, and asked them to keep track of the number of hours spent using the device, and the proficiency with which the infant used the walker. Our goal was to test the infant after a minimum of 40 hours of forward movement in the walker device.

In this study, some of the infants provided with walkers began to locomote spontaneously just as, or just before, they reached the minimum criterion we required for testing. Accordingly, we had two groups of infants with walker experience: one group that was truly prelocomotor when tested on the visual cliff, and one that had a minimal amount (an average of five days) of endogenously-determined crawling experience. To assess the influence of locomotor experience in this study, we obtained two additional groups matched in age, locomotor experience, and socioeconomic status, creating four groups in all: 1. prelocomotor walkers, 2. locomotor walkers, 3. prelocomotor controls, and 4, locomotor controls. In this study, all four groups averaged the same age at the time of testing – just over seven months.

As in the previous study, all infants were tested using the descent paradigm. Results showed significant and dissociable effects of artificially-induced self-produced locomotor experience, and of spontaneously acquired experience on cardiac responding on the deep side of the cliff. More specifically, prelocomotor infants with artificial walker experience showed a significantly different heart rate pattern upon descent than did their matched prelocomotor controls. As can be seen in Figure 2, walker infants showed a steadily-rising cardiac acceleration upon descent toward the deep side, which contrasted with a nonsignificant deceleration shown by the prelocomotor controls.

The pattern of cardiac responding shown by the infants with both artificial walker experience and a few days of spontaneous locomotion was even more striking. All 17 infants in this group showed cardiac acceleration, and the group data showed a trend toward a significantly greater acceleratory response when the infants were lowered onto the deep side of the cliff than was shown by those who had either the same amount of experience crawling but no walker experience, or had walker experience, but no experience crawling. A "double dosage" of locomotor experience, then, produced a particularly strong acceleratory cardiac response on the deep side of the cliff. These results from the "enrichment" manipulation were entirely consistent with the predicted effect on visual cliff performance.

More recently, we had the opportunity of longitudinally examining an orthopedically handicapped child who was born with two congenitally dislocated hips and who was placed in a full body cast after an early operation to correct the defect. The infant showed no signs of any neurological problems, and was tested at a Developmental Quotient of 128 on the Bayley Scales. We began testing this infant at six months of age, and continued testing once a month until the child was 10 months of age. During the first two months of testing, the child remained in the cast and showed no evidence of crawling or creeping. Prior to the third visit, the cast was removed and the child was placed in a Pavlik harness – an orthopedic device much lighter than a cast that allows some movement of the upper body. While in the Pavlik harness, what movement the child engaged in appeared quite limited and very effortful – not likely to provide the equivalent of normal locomotor experience. By the fifth visit, the harness was removed and the child began to crawl freely.

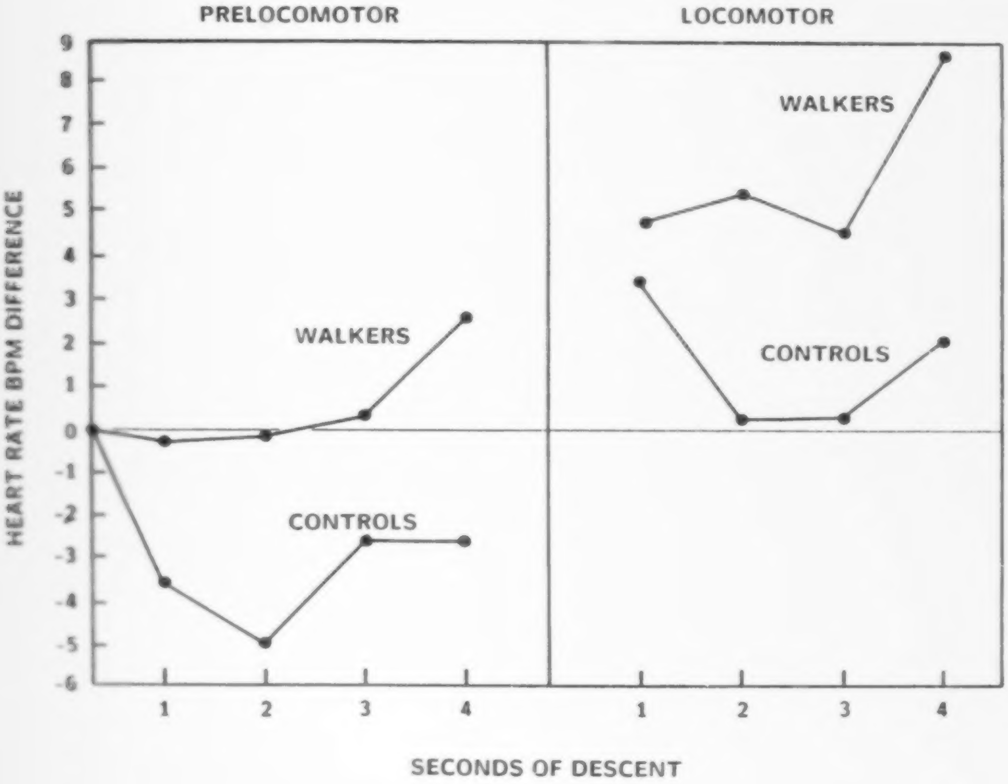

Fig. 2. *Second-by-second heart rate changes of subjects as they were lowered to the deep side of a visual cliff. Data are grouped according to whether subjects had locomotor experience provided by walkers or not, and also whether they had spontaneous locomotor experience or not. The ages of subjects in the four groups were identical.*

We were able to test the child on the visual cliff monthly, and discovered no differences in heart rate response on descent to the two sides of the cliff at any age until the last one – when the infant was 10 months old and had experience crawling. At 10 months, the infant's heart rate on the deep side shifted to a marked acceleration indicative of fear, whereas the heart rate response on the shallow side became deceleratory.

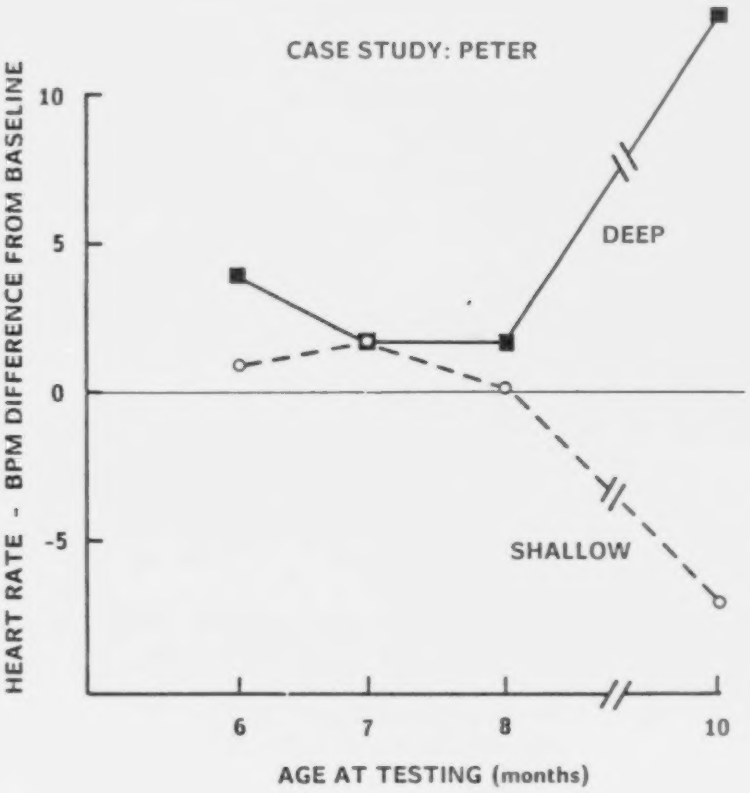

Fig. 3. *Mean heart rate changes of an orthopedically-handicapped infant at different ages, demonstrating a cardiac developmental shift on the visual cliff as a function of the removal of a cast and the initiation of crawling. At 8.5 months of age, the Pavlik harness was removed 4 hours a day, permitting some self-produced locomotion.*

Although we recognize the limitations of making inferences from a single case study, these findings provide further support for the notion that wariness of heights emerges subsequent to the emergence of self-produced locomotor experiences.

Because all the studies with the visual cliff described above utilized the descent paradigm and heart rate as the dependent variable, it is possible to argue that one will obtain different findings with the more traditional locomotor crossing paradigm, in which locomoting infants are called by their mothers to cross the deep or the shallow side to get to them. To test whether a locomotor crossing paradigm shows functional relations with locomotion similar to those obtained with the descent paradigm, we employed a lag design and determined whether it is the age of onset of locomotion or amount of locomotor experience that accounts for visual cliff avoidance behavior.

In this study, mothers were contacted when infants were 5 1/2 months of age, and were instructed to call us as soon as each infant had begun to move about on his or her own. Infants were then brought into the lab when they had either 11 or 41 days of locomotor experience. We blocked the age of onset of locomotion into three groups for the purpose of analysis: age of onset at 6.5 months, 7.5 months, or 8.5 months (plus or minus two weeks in each case). There were 16 infants per group, and six groups in all (three ages of locomotor onset by two levels of locomotor experience).

The results of this study, which are presented in Figures 4 and 5, clearly document the importance of locomotor experience and not age of onset of locomotion as the factor related to the increase in avoidance of crossing the deep side of the cliff. Regardless of the age when the infant began to crawl, approximately 30-45% of the infants avoided crossing the cliff to get to the mother when those infants had only 11 days of locomotor experience. However, when infants had 41 days of locomotor experience, approximately 60-80% of infants avoided crossing the deep side. Statistical analyses revealed significant effects of locomotor experience, but not age, regardless of whether one used nominal data for analyses (cross/no cross), or interval data (the latency to descend off the center board of the visual cliff apparatus). In short, the descent paradigm and the locomotor crossing paradigm converge in documenting that increases in wariness of heights typically follow the onset of crawling.

Processes underlying the developmental changes in fear of heights: One question which the research on the visual cliff does not answer is how the fear of heights originates – where the "affective sting" comes from, as it were. At one time, the mere perception of "depth-at-an-edge" was considered to be a sufficient stimulus for fear of heights, but the perception of height by itself does not necessarily lead to fearfulness. Early research with the visual cliff has shown that infants can be very sensitive to a dropoff, showing consistent cardiac decelerations to the deep side, without showing any facial evidence of wariness of heights (Campos et al., 1970; Campos & Langer, 1971).

As mentioned earlier, falling experiences are plausible candidates as determinants of the development of wariness. However, unpublished longitudinal studies in our laboratory have not succeeded in linking the presence of falling experiences to the avoidance of crossing the deep side. Mothers are just as likely to report a major fall prior to a test in which the infant crosses the deep side, as not to report a major fall and have the infant avoid crossing.

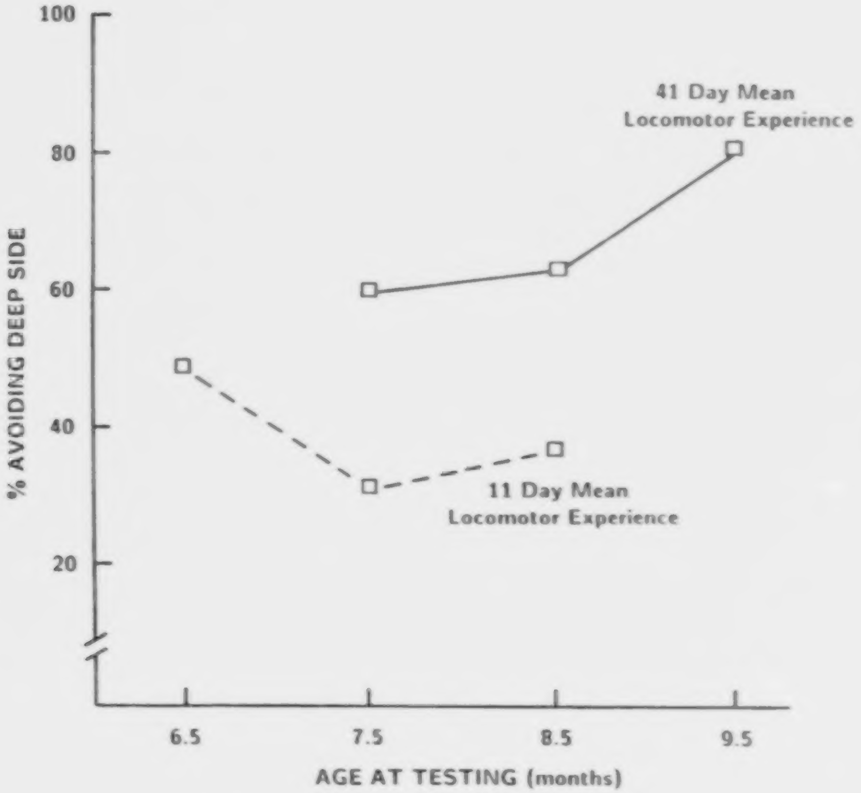

Fig. 4. The percentage of subjects who avoided any descent onto the deep side of the cliff as a function of both locomotor experience and age.

At present, we favor three general mechanisms for the development of fear of heights following the acquisition of locomotor skills. One mechanism stresses emotional communication from the mother to the child in contexts of danger; the second emphasizes the more complete coordination of vision with vestibular stimulation upon the acquisition of locomotion; and the third deals with the functional "expansion" of the visual field in the third dimension, resulting in infants showing an improved understanding of perceived changes in the spatial layout.

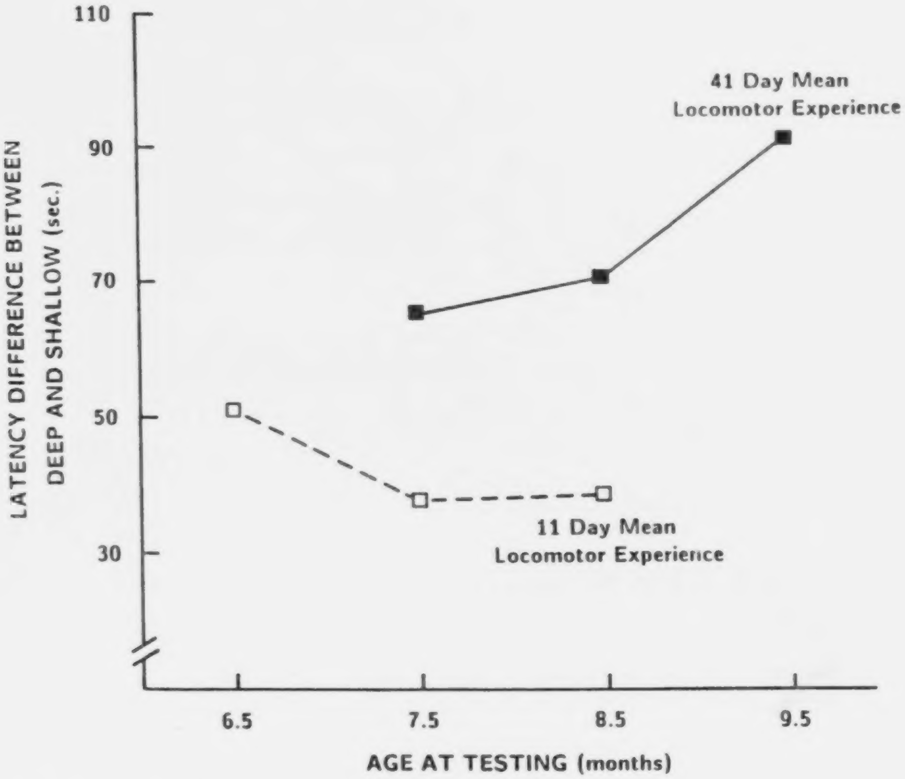

Fig. 5. *Latency to descend all four limbs onto the deep or the shallow side of the visual cliff as a function of both age and locomotor experience.*

Emotional communication: A child need not fall when locomoting to experience the emotion of fear. Locomotion serves to place the child in settings where the child is in a position to fall. As we noted above, mothers typically report that there is a stage when infants will readily go off a high place if the mother is not there to watch the child and protect him. One way that the mother protects her child is by vocalizing in a fearful way when the child is in danger of falling. Such vocalizations can engender fearfulness directly in the child; the child can then link the vocalization to the setting he was in, and develop a vicarious fear of heights in this manner.

We know from studies of social referencing that emotional communication can powerfully regulate the infant's behavior in here-and-now contexts (Klinnert et al., 1982; Sorce et al., 1985). For example, the mother's posed fearful facial expressions alone can lead a 12-month-old infant to avoid crossing a modified visual cliff, and that fearful or angry vocal expressions alone can inhibit an 8.5-month-old infant from approaching a toy. What remains to be demonstrated is that infants at the ages we have studied with the visual cliff can retain the effects of the emotional communication and remember to fear heights, and that they can generalize such retention to new contexts, such as the visual cliff table.

Coordination of visual-vestibular relations: Important as emotional communication may be in the development of fear of heights, it is not likely to account for all instances of such fear. The actively-moving kittens in the Held and Hein kitten studies avoided the deep side of the visual cliff, yet the conditions of dark-rearing precluded their having acquired the fear of heights through social communication. Because vestibular stimulation is such a strong elicitor of emotional reactions (Izard & Malatesta, 1987; Russell, 1979; Watson & Morgan, 1917), we suspect that it may be playing a role in the emergence of the fear of heights. To account for the empirical findings from our laboratories, the role of vestibular stimulation in eliciting the fear must (a) occur in conjunction with vision, since the fear is visually-elicited, (b) principally follow the onset of locomotion, and (c) be observed even in the absence of actual loss of support. Consequently, we propose, first, that one of the effects of the acquisition of self-produced locomotion is a much greater correlation of visual and vestibular feedback to the child, and secondly that decoupling of such coordination can elicit negative emotions. We will now elaborate on these two propositions.

The notion that forward locomotion must result in a much better coordination of two sources of information about self-motion follows from the way in which vision and vestibular information specify self-movement. Vision specifies self-movement by the progressive expansion and acceleration of the optic flow on the periphery of the visual field. When a person is looking in the direction in which he or she is moving, the optical flow emanates from a central point of origin (the target of movement), and reaches its peak 90° in all directions and around the subject's visual field. Such optical flow patterns constitute the information that makes a seated theater patron feel as if moving when watching certain wide-screen visual displays. Vestibular stimulation, by contrast, specifies direction, acceleration and deceleration of movement independently of the subject's focus on the target of movement. Early in life, prior to goal-directed self-propulsion, the coordination of visual and vestibular information about self-motion is very imperfect because the pre-crawling infant's movements are under the control of others; the child is unlikely to be looking consistently in the direction of forward motion (and obtaining expanding and accelerating visual inputs) until the child's movements become self-directed. Upon the onset of locomotion, visual and vestibular inputs come to specify the same state, and thus these inputs become better correlated. Important changes in visual-vestibular coordinations thus ensue from the onset of crawling, as well as from the pre-crawling infant's mastery of goal-directed "walker" activities.

Once coordinated, the decoupling of visual and vestibular inputs sets the stage for the elicitation of negative effect. Such decoupling can take place, for instance, when the observer remains stationary, and experiences global optical flow (Butterworth & Cicchetti, 1978; Dichgans & Brandt, 1978; Lee & Lishman, 1975; Nashner, 1972). It can also take place in situations with insufficient visual information (for example, closing one's eyes), at which time postural sway increases. In either case, the decoupling may elicit negative affect directly, as a result of the visual-vestibular discrepancy itself, or indirectly, from the vestibular changes that follow the compensatory postural shifts (Lee & Lishman, 1975; Nashner, 1972).

These facts apply to the visual cliff situation in the following way. Both anterior-posterior and lateral body sway are detected by the motion of visual contours on the retina (Leibowitz & Post, 1982). When the closest visible contours are at a greater distance than normal, such as occurs when looking at the bottom of the cliff, there occurs greater body sway before the retinal motion is detected, and some coordination of visual with vestibular information is again achieved. The infant thus may detect a discrepancy from customary visual-vestibular feedback. In addition, with greater body sway, there should follow increased stimulation of the vestibular system when the infant is placed over or on the deep side of the cliff. This increase in vestibular stimulation then may also be sufficient for eliciting fear in the infant.

Unfortunately, our studies to date have not recorded infant postural adjustments on the cliff. As a result, we are not able to evaluate our hypothesis with existing data. Nevertheless, our reasoning leads us to predict that if prelocomotor infants were to be given extensive experience locomoting in the direction of head orientation, they would show precocious visual cliff performance–i.e., wariness of heights even before the onset of locomotion, since they would have much greater coordination of visual with vestibular stimulation. We also predict that if locomotor infants were placed in another situation besides the visual cliff in which vision and vestibular information were uncorrelated, they would likewise show fear. For instance, we predict that locomotor infants are much more likely than prelocomotor infants to show cardiac accelerations in a "moving room," in which the walls move back and forth, but the floor on which the child stands remains stationary. We are at present testing these predictions.

Development of spatial understanding: The third proposed mechanism suggests that experience locomoting results in important and unsuspected changes in visual processing of the spatial layout. For instance, locomotion can facilitate the calibration of distances, resulting in a better appreciation of the distance that something is from one's body (Kaufman, 1979). Also, as discussed by Piaget (1954), the infants slowly construct an understanding of "far space" as they develop motorically and cognitively. This latter development, in particular, follows logically from some of the new demands imposed by self-produced locomotion on the infant. Most importantly, the locomoting infant must pay greater attention to changes occurring in the visual surround, as well as to the self; otherwise, he would be continuously bumping into other objects. As a consequence of this increased attention, the infant is likely to detect new relations between his own movements and changes in the spatial layout. For example, the infant will be more likely to appreciate how different actions will lead to different consequences upon perceiving depth at an edge.

These proposed changes underscore the need to distinguish between simply detecting information about the third dimension, and understanding the significance of this information. Although we know that infants have excellent stereopsis by 3.5 months, and show highly reliable visually guided placing reactions on the shallow side of the visual cliff by six months of age, no study yet done has adequately addressed the possibility that with locomotion, the effective visual field of the infant "expands" in the third dimension, resulting in the infant better detecting distance information (e.g., detecting new sources of depth-specifying information) and more frequently directing his attention to distances. In general, much more is known about detecting depth information than how the actions of the infant are affected by this information (Campos et al., 1978; Fox, 1980; Kagan et al., 1978). Clearly, the finding that self-produced locomotion leads to the development of the infant's wariness of heights underscores the need for more precise study of mechanisms of spatial-affective development.

The development of spatial orientation

Self-produced locomotion has often been linked by various theories to changes in spatial understanding, in particular, to the organism's appreciation of the layout of spatial information (Gibson & Spelke, 1983). In this section, we review work showing the powerful effects of self-produced locomotion on spatial understanding in infants. Specifically, we will discuss the consequences of self-produced locomotion for developmental changes in two crucial spatial processes in infancy. First, we will discuss the link between experience creeping on hands and knees and success in manual search tasks involving memory for locations, especially those tasks that involve more than one hiding site. Then, we will discuss the link between locomotor experience and the shift from egocentric to allocentric coding strategies (i.e., the change from use of body-centered spatial coding strategies, such as localizing objects to the left or right, to strategies which permit localization of objects by reference to stable environmental landmarks).

Manual search performance as a function of locomotor experience: One of the best-known features of the cognitive development of the 7-9 month-old infant is the apparent emergence of an ability to search for an object hidden under one or more covers. The phenomenon, traditionally considered to reflect the beginnings of object permanence, was given theoretical importance by Piaget (1954), who proposed that the child's pattern of search revealed an incomplete understanding by the infant of the spatial relations among objects in the outside world. For example, infants at this age frequently err in searching when there is more than one hiding place, and often perseverate in searching for an object at a location where the child was previously successful, rather than at a new location where it was visibly hidden (Piaget, 1954; Kagan et al., 1978).

There is now evidence that aspects of Stage 4 search behavior are linked to the development of self-produced locomotion. In a study done nearly ten years ago, the objective of which was to relate object permanence development to the development of fear, an unexpected relation was obtained between the development of crawling and the development of object permanence (Campos et al., 1978). Infants with crawling experience, almost without exception, demonstrated Stage 4 or higher object permanence development, showing no difficulty in finding completely hidden objects in one or sometimes two locations; by contrast, infants without crawling experience were typically in Stage 3, demonstrating only the ability to find a partially, but not fully, hidden object. Some prelocomotor infants were in Stage 4, though, suggesting that locomotor experience is not *necessary* for advanced object permanence performance. In connection with the possibility that locomotor infants may have been more mature than prelocomotors in this study, it is important to note that *age* was not a factor, since both locomotor and prelocomotor infants were 7.3 months old.

More recent and more direct evidence points to the same type of relation between locomotion and spatial search patterns in an object permanence task. Horobin and Acredolo (1986) reported finding a relation between locomotor experience and search patterns in an object permanence task. They noted that infants with *more* experience moving around on their own were *less* likely to make the AB error, and hence to avoid searching perseveratively at a location where an object was no longer hidden. Their findings thus suggest that with greater locomotor experience infants increasingly use external cues to guide their search, and steadily abandon the tendency to retrieve objects based on response perseveration.

Importance of movement for spatial search performance: Why should self-produced locomotion prompt a higher level of spatial search behavior or object permanence performance? We believe that a fundamental sensory-motor skill underlying object permanence development is experience with kinetic occlusion. This phenomenon, of course, refers to the relative displacement of two or more objects, in which a nearer object first obscures, then uncovers, a more distant object. Occlusion thus permits the child either to discover, or to become much more sensitive to, the relationships of "in front" and "behind," as well as "on top of" and "below."

Although occlusion is noticeable by prelocomotor infants when they move their heads while seated, or when they are moved about passively, it is likely that self-produced locomotion generates more frequent, more pervasive, and more salient instances of this event than do head movements. In other words, we are postulating that the crawling infant is more likely to notice information about spatial displacements, including occlusions and reappearances, than is the prelocomotor infant.

If self-produced locomotion facilitates the detection of occlusions and reappearances of objects, and if such detection, in part, underlies the development of search for hidden objects, the acquisition of crawling abilities may facilitate the development of Stage 4 object permanence search behavior. In this regard, it is noteworthy that there is a very close correspondence between the mean age of onset of development of self-produced locomotion (which the Bayley Scales place at 7.1 months), and that for the development of search for a hidden object, which Uzgiris and Hunt (1975) place at the same age.

Another process that may link the development of crawling and creeping to object permanence is attentional deployment. This process is not necessarily inconsistent with Piaget's theory emphasizing intercoordination of sensory-motor schemes, but implies different sets of observables to focus upon in studying developmental changes in object permanence performance. The work of Horobin and Acredolo (1986) again proves relevant in this regard: they found that the more attentive infants in their study were those who had the greatest experience moving around on their own.

It has also been our impression, based on testing infants in object permanence-like tasks, that locomotor infants are far more attentive to hidings and uncoverings (keeping their eyes and heads oriented more frequently toward the hiding place), and much less distracted by other environmental stimuli than are prelocomotor infants.

Although there is no research that we are aware of linking heightened attention to development of locomotor skills, it is clear that upon acquiring locomotor abilities, the child may need to become more focused in deployment of attention. For example, to attain a goal located several feet away, an infant must engage in more "steps" between where he is at time A, and where he wants to be at time B. Such increases in time between activation of means and attainment of end must be accompanied, and perhaps mediated, by greater attentional persistence. There is evidence from the work of Kellman (1985) that passive movement of a prelocomotor infant around an object produces attentional levels characteristic of stationary observers. Passive movement may thus not be especially effective in mobilizing attention toward environmental events correlated with such movements. Indeed, we have observed that when moved passively, even older infants do not seem to focus their attention on a single object, and thus are unlikely to profit from occlusion and reappearance information, even though that information is potentially available to them. Passive locomotion seems to be associated with the infant entering a state of "visual idle," in which the child stares blankly into space.

It is possible that after the onset of locomotion, attentional persistence generalizes even to non-locomotor tasks such as object permanence. In brief, the greater goal-orientation possible for the locomotor child may result in greater motivation to stay "on task." If so, and if part of the variance in object permanence performance seems critically related to the infant's ability to attend to the location where an object is hidden, then greater attentiveness should result in superior object permanence performance (Goldfield & Dickerson, 1981).

Spatial search, and self-produced locomotor experience: The link between the development of self-produced locomotion and object permanence performance was recently investigated by Kermoian and Campos (in press). In this study, clear functional relations were reported between degree of locomotor experience and success in manual search using a variant of a task reported by Kagan, Kearsley, and Zelazo (1978). Infants were categorized into three groups: prelocomotor with no "walker" experience (N=32), prelocomotor with "walker" experience (N=32), and locomotor (N=32). Moreover, we interviewed mothers to determine the extent of locomotor experience their infants had, either spontaneously, or with "walkers." This permitted us to determine the relation between amount of experience locomoting and level of memory for locations performance.

The tasks the infants were presented involved, in increasing order of difficulty, a partial hiding, a hiding under one cover, under one of two covers, under one of two covers with increasing delays between hiding and search, and trick hidings where the object disappeared or was switched. A full description of each of the tasks used in this experiment is provided in Table 1.

The findings of this study are presented in Figure 6, and confirm that self-produced locomotion is closely linked to manual search performance. Note three important findings in Figure 6. First, prelocomotor infants and infants with three weeks or less of locomotor experience perform at relatively low levels on the manual search tasks. The major problem shown by prelocomotor infants and infants locomoting for only a brief period of time concerns the effects of a second cover. Although these infants can often correctly search for an object hidden under a single cover, they have great difficulty searching correctly for a hidden object if a second cover is available. It appears that the presence of the additional cover (even if never used to actually hide a toy) distracts or confuses the prelocomotor infant, as well as those with minimal locomotor experience.

Secondly, beyond three weeks of locomotor experience, whether "artificial" or spontaneous, more locomotor experience is associated with higher levels of performance on this set of search tasks than is shown by prelocomotor infants.

Finally, neither age nor any other maturational factor can solely explain these findings since age was held constant, and the performance of the prelocomotor infants with "walker" experience was very similar to that of crawling infants.

These findings are especially significant because Kagan, Kearsley, and Zelazo (1978) attribute to maturation of the frontal lobes of the brain changes in performance on this spatial localization task. By contrast, the preliminary data obtained by both Campos et al. (1978) and by Kermoian and Campos (in press) suggest an epigenetic rather than a maturational interpretation. It appears that a process under partial biological control (locomotion) permits new experiences to take place, and these in turn mediate certain developmental outcomes. Although it may be true that these outcomes may be associated with structural changes in the frontal lobes, such cortical changes may not occur independent of quite specific environmental stimulation. Rather, changes are mediated by specific experiences, and locomotion appears to function as one of the experiences that generate new neurophysiological structures (Greenough et al., 1987).

Locomotion and performance on two-position hiding tasks: We have recently obtained data confirming Kermoian's and Campos's findings on the difficulty that prelocomotor infants have in searching correctly for an object hidden in one location when a second hiding location is also present (Campos et al., 1986). In this study, a variant of the Bremner and Bryant hiding task was used, in which 8-month-old infants are seated in a high chair mounted on wheels in front of a table containing two submerged hiding wells (Bremner & Bryant, 1977). Perceptually-distinct covers (one white, one black) were used to hide the target object after it was placed in one of the submerged wells. As in other studies, infants were assigned to one of three groups: prelocomotor (N=24), prelocomotor with walker experience (N=12), and endogenously crawling (N=16).

The major finding in this study was that locomotor experience, whether endogenous or artificially-induced, significantly facilitated correct search in the two position hiding task. Locomotor infants searched correctly on 72% of the hiding trials, walker infants searched correctly on 68% of the trials, and prelocomotors searched correctly on only 22% of the trials. Manual search for hidden objects (i.e., what was once referred to as Stage 4 of object permanence) thus appears to show a consistent relation to self-produced locomotor experience, and this finding cannot be attributed to maturational factors since prelocomotor infants with walker experience performed at a level similar to crawling infants.

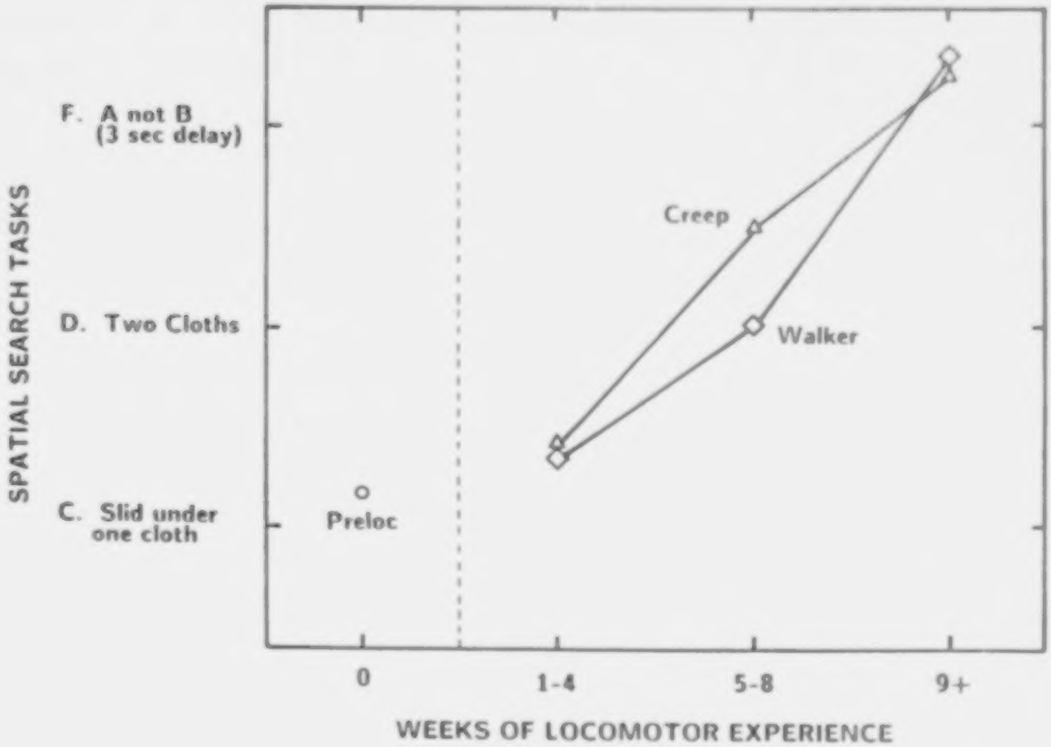

Fig. 6. *Memory for locations performance of prelocomotor infants with no artificially-induced locomotor experience, prelocomotor infants with different numbers of weeks of spontaneous locomotor experience, and locomotor infants with different number of weeks of spontaneous locomotor experience. Task items have been ordinally scaled, and were adapted from Kagan, Kearsley, and Zelazo (1978).*

TABLE 1: DESCRIPTION OF TASKS IN KERMOIAN AND CAMPOS STUDY (in press)

1. Object half-hidden under one cloth. The examiner moved the toy along the tabletop, eventually sliding it under a single cloth located directly in front of the infant until the object was only half visible.

2. Object hidden under one cloth. The examiner slid the toy under a single cloth located directly in front of the infant until the object was no longer visible.

3. Object hidden under one of two identical cloths. The examiner slid the toy under one of two identical cloths. The cloths were located five inches apart, each 2.5 inches to the right and left of the infant's midline.

4. A not B task with a three second delay between hiding and search. The examiner slid the object under one of two identical cloths. After the infant had retrieved the object under one cloth on three consecutive trials, the mother was asked to hold the infant away from the table while the examiner hid the toy under the second cloth. Three seconds after the object had disappeared, the mother was asked to release the infant.

5. A not B task with a seven second delay. The A not B procedure was followed with a seven-second delay between the time the toy disappeared under the cloth, and the time at which the infant was allowed to search.

6. AB test with 3 sec delay, and object absent from hiding location. The A not B procedure with a three-second delay between the time the toy disappeared under the cloth, and the time at which the infant was allowed to search. However, when the infant looked under the cloth where the toy had disappeared, the toy was no longer present. To pass this item, the infant needed to show continuation of search.

7. A not B task with an object substituted for the one originally hidden. The A not B procedure was followed without a delay between the time the toy disappeared under the cloth and the time at which the infant was allowed to search. However, when the infant looked under the cloth where the toy had disappeared, there was an object the infant had not seen previously. To pass this item, the infant must have demonstrated surprise.

Note. The seven tasks form an ordinal sequence. Tasks were administered sequentially.

Locomotor impediment delays correct spatial search until crawling onset: The same functional relation between spatial search and locomotion was found with infants showing serious locomotor delays (Telzrow, 1986). Dr. Robert Telzrow, of Children's Hospital and the University of Washington, longitudinally tested seven children with myelodysplasia on the same two-position spatial search task just described (Campos et al., 1986). Myelodysplasia is a serious neural tube defect that results in a variety of motoric difficulties, including marked delays in the onset of crawling. When such children have lesions located low in the spinal cord, the onset of crawling does not occur until about one year – some five months later than expected in the normal baby. With this documented delay in their gross motor function, these children presented Dr. Telzrow with an opportunity to test the relation between self-produced locomotion and the emergence of skills assessed in tests of spatial search.

Seven children were tested longitudinally, at approximately monthly intervals, beginning, whenever possible, at six months of age. All seven children eventually met the criterion for self-produced locomotion, which Telzrow set as the ability to move four feet within two minutes with apparent intent. The mean age of attaining this locomotor criterion in the Telzrow sample was 10.35 months, with a range from 8.5 to 13 months.

Telzrow's results are summarized in Figure 7, which graphs the success rate in the two-position hiding task as a function of pre- or post-locomotor status. The pre-locomotion mean represents the percentage of success in the two months before locomotion independent of age (six correct searches out of 40 trials), and the post-locomotion mean represents the percent success for the two months following at least two weeks of self-produced locomotion (54 correct searches out of 75 trials). It is thus clear from Telzrow's work that (a) developmental delays in onset of crawling result in persistence of low levels of spatial search performance, (b) the onset of crawling forecasts the onset of successful spatial search in a two-position hiding task, and (c) it is crawling and not age that accounts for this developmental shift. This study thus provides additional evidence for the importance of locomotor experience as an organizer of changes in spatial cognition.

Locomotor experience, and the shift from place to response learning: Between six and nine months of age, infants undergo a shift in spatial coding strategies. Early in the second half-year of life, infants typically (though not exclusively) localize objects egocentrically, i.e., by reference to the object's location relative to the infant's body (e.g., to the infant's right or left). By nine months of age, infants begin to code objects more consistently in an objective manner (i.e., by reference to spatial landmarks).

Self-produced locomotion is likely to account at least in part for such a change in coding strategies because locomotion renders egocentric coding strategies inefficient and inaccurate. That is, so long as the infant's body is relatively static, coding of the position of fixed objects by reference to the body will rarely lead to error. However, once the child begins to move about on his own, an object can no longer be expected to be locatable to the infant's left or right. Locomotion can lead to the object being to the infant's right at one time, to the left at another, and so on. Such locomotor experiences might thus lead to the infant abandoning response-based strategies in favor of landmark-based strategies.

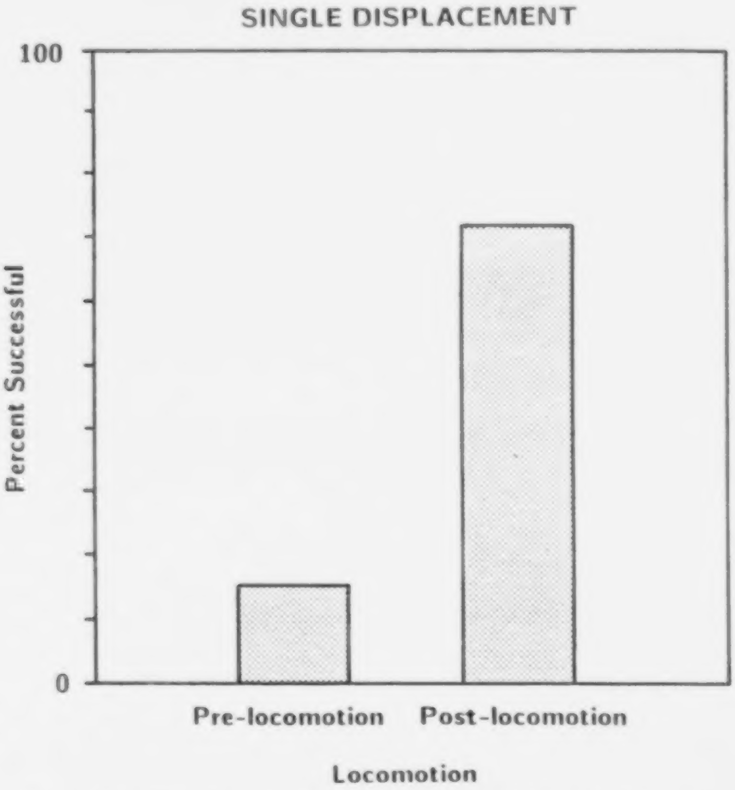

Fig. 7. *Correct search for an object hidden in one of two locations before and after the onset of locomotion. Subjects were infants with spinal lesions delaying locomotion until after 10 months of age.*

This shift in spatial coding can be readily tested through the use of spatial rotation tasks. Such a task involves two phases. In the training phase, the infant learns to anticipate the appearance of an interesting sight at a location that is specified both by a landmark, and by a constant location relative to the infant's body (e.g., it is always to the right). In the test phase, the infant is rotated 180 degrees in order to dissociate place from response learning. If the infant shows evidence of response learning (i.e., the infant turns in the same physical direction – right or left – as before) the infant will look at the wrong place. If the infant shows evidence of place learning (i.e., the infant turns toward the opposite direction as before, to the landmark-specified location), he will turn toward the location where the reinforcing stimulus had previously appeared.

Acredolo (1978; Acredolo & Evans, 1980) used such a paradigm to test for spatial localization in infants. In our modification of her paradigm, infants were situated in a square, curtained, 8 x 8 foot room, consisting of four solid, gold-colored opaque drapes hung from ceiling to floor. Located in the center of two opposite sides of the enclosure were two identically-sized 11 x 9 inch cut-out windows which were covered from outside the enclosure with white cloth curtains. One of these windows was encircled by a variety of landmarks, including a bright blue cardboard star, a string of clear blinking Christmas tree lights mounted on a green wooden frame, and 8 green crepe paper stripes hung from ceiling to floor along the entire side of the enclosure. The opposite window had no landmarks of any sort.

The infant was seated on a feeding table (a high chair with a surrounding table top) mounted on a wooden platform with wheels. From this seat, the landmark and the no-landmark windows were at a 45 degree angle from the infant's midline. There were 60 infants in this study, equally distributed among prelocomotor, prelocomotor with walker experience, and locomotor groups. The infants were eight months of age, plus or minus 8 days.

Training consisted of a buzzer signaling the appearance of a brightly-colored hand puppet from the landmark window after a delay of three seconds. During the next ten seconds, the experimenter spoke to the infant until the curtain was closed again. When the infant had learned to anticipate the experimenter's appearance on four of five consecutive trials, the mother, who was standing behind the infant's chair, was signaled to rotate the position of the chair 180 degrees by moving it to the other side of the room. The infant was then given five test trials in which the buzzer was sounded, but the experimenter did not appear. Two observers coded the direction of the infant's head movements following the buzzer.

As was found in the studies of manual search described above, locomotor experience affected spatial coding strategies. Following rotation after the training criterion had been met, locomotor infants turned toward the correct spatial location on 46% of trials, prelocomotor infants with walker experience responded correctly on 40% of trials, while locomotor infants responded correctly on only 24% of trials. Data analyses are continuing in this study; however, our preliminary findings indicate that with locomotor experience, infants become more likely to use allocentric or objective spatial orientation strategies, and less likely to use body-centered or egocentric strategies.

Interestingly, the orthopedically handicapped infant described in the section on the visual cliff also provided evidence of the importance of locomotor experience for producing a shift in coding strategy. When tested in a paradigm that was virtually identical to the one just described, this infant responded egocentrically on 60 to 100% of the test trials. Upon acquiring the capacity to locomote, the child's egocentric response level dropped to 0% (Bertenthal et al., 1984). Thus, both the enrichment (walker) manipulation and the deprivation (handicapped infant) study converge in linking changes in spatial coding to the acquisition of self-produced locomotor experience.

Future Directions for Research on Self-Produced Locomotion

We believe these findings on the consequences of the development of self-produced locomotion for emotional development and for spatial understanding have many other implications which have not been adequately considered by infancy researchers. The developmental shift on the visual cliff raises the possibility that for whatever reason the infant may demonstrate an expansion of his visual world in the third dimension – a phenomenon which Piaget described as the infant's slow appreciation of the difference between near space and far space.

One important aspect of the child's gradual appreciation of the relation of environmental objects to one another has relevance to language development. Between eight and ten months of age, the child shows a shift in understanding pointing gestures from first looking at the finger that is doing the pointing, to extending the look to the referent of the point. Does the acquisition of self-produced locomotion facilitate this developmental transition? If so, then crawling may have consequences, albeit very indirect ones, even for language development, given the significance of pointing gestures as a nonverbal origin of semantic understanding (Werner & Kaplan, 1963).

Still another important developmental change which we would expect in the infant upon the acquisition of self-produced movement is a shift in emotional communication. The child necessarily becomes more demanding to the mother as he or she begins to explore numerous objects such as plants, vases, electric outlets and other environmental stimuli which require caution or prohibition. Accordingly, the child must become the object of sharply increased, and probably more negative, distal communication from the caregiver (Bertenthal & Campos, in press).

These considerations demonstrate all too briefly the significance of self-produced locomotion and point to the importance of exploring the consequences of the acquisition of motoric skills such as crawling and walking.

Above and beyond any specific findings, our own efforts in this endeavor have provided us with a greater appreciation of the power of conceptualizing human development as an epigenetic process.

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VISUAL-VESTIBULAR INTEGRATION IN EARLY DEVELOPMENT

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Abstract

The goal of this paper is to explore some of the mechanisms by which the infant perceives self-motion, as well as to examine how these mechanisms change with crawling experience. It is proposed that visual information in the form of optical flow is fundamental to the perception of self-motion, and that it is mediated primarily by the retinal periphery. Moreover, it is argued that the onset of self-produced locomotion necessitates changes in the way that self-motion is processed. A series of experiments are described that test the validity of this proposition for infants. These experiments use a "moving room" – a small room in which the walls and ceiling can be moved while the floor remains stationary – to assess whether or not infants show postural compensations to the perceived optical flow. Collectively, the results from the different experiments suggest that (a) infants show sensitivity to global optical flow for specifying their own self-motions and controlling their posture by 7 months of age, (b) peripheral optical flow is sufficient for specifying self-motion and postural stability by 9 months of age, and (c) experience with both sitting and standing postures contributes to increased stability under conditions of sensory conflict. The final section of this paper discusses some important clinical implications of this research.

One of the most significant milestones of early development is the acquisition of self-produced locomotion or crawling(Bertenthal et al., 1984). There is by now considerable data showing that early crawling experience plays a fundamental role in the development of a number of other skills, including object localization, spatial orientation, fear of heights, and social referencing (Acredolo et al., 1984; Campos & Bertenthal, 1987). Surprisingly, however, the processes by which these functional relations develop is poorly understood. It is our contention that forward progress on this issue demands a more complete understanding of the specific processes governing locomotion (Campos & Bertenthal, 1987).

At a general level, there are two related processes that mediate the forward propulsion of the human infant: (a) control and coordination of muscles and joints into appropriately organized response patterns, and (b) monitoring sensory information to ensure that responses remain context dependent. It is the latter process that is most relevant to the following discussion. In essence, our goal in this chapter is to explore the mechanisms by which the infant perceives self-motion, as well as to examine how these mechanisms change with crawling experience.

Visual-Vestibular Integration in Adult Observers

Our analysis begins with an overview of how self-motion is detected by a moving person. In the normal human adult, postural changes are directly detected from mechanical and vestibular stimulation because of the inertia of body constituents (Lishman & Lee, 1973). The vestibular system registers angular accelerations of the head around three orthogonal axes and linear acceleration along another axis on the basis of the fluids contained in the semicircular canals and otoliths. At a more global level, the joint receptors and muscle stretch receptors, if considered as a system, are capable of registering accelerations of the body because of the inertia of the limbs. In both cases, the direction of these changes is registered relative to an inertial-gravitational frame of reference.

Note, however, that many movements, especially those involving locomotion, need to be guided relative to an environmental frame of reference. Thus, it should not be surprising to find that visual input also specifies information about body sway and self-motion (Gibson, 1979). As an observer moves through the environment, there occurs a global flow of optical texture that is congruent with the direction and velocity of the movement. Instead of perceiving this stimulation as movement in the environment, stationary observers report that this form of visual stimulation is consistent with the perception of self-motion (Dichgans & Brandt, 1978). Everyday examples of perceiving this form of stimulation as self-motion abound. For example, sitting in a stationary train while a train on the adjacent track begins moving produces a perception of self-motion.

It is important to note that even though there are multiple sources of sensory information for specifying self-motion, they are not equally satisfactory across different stimulus conditions. Consider, for example, the differences between active and passive movement in illuminated and darkened environments. Both forms of movement are veridically perceived as long as the environment is sufficiently illuminated. Conversely, passive observers in a darkened environment or one without much visible texture experience considerable difficulty in continuously monitoring their movements, especially when moving at a constant velocity. For example, a passenger in a moving vehicle at night will find it difficult to perceive either the speed or direction of movement. Situations such as the preceding one are useful for exposing some of the deficiencies of the vestibular system for specifying self-motion. Vestibular information about motion is evoked only through accelerations or decelerations, and thus, becomes increasingly uninformative as the cupulae in the semicircular canals, or the otoliths progressively return to their resting position under constant velocity (Dichgans & Brandt, 1978). Yet, self-motion is perceived regardless of whether it is registered by only the visual system or by both the visual and vestibular systems.

Dichgans and Brandt argue persuasively using both psychophysical and neurophysiological data that the sufficiency of the visual inputs for perceiving self-motion implies that the visual and vestibular inputs must converge at some locus in the neural pathways where they are integrated to provide a common basis for postural compensations and other forms of dynamic spatial orientation (Dichgans & Brandt, 1978). It is specifically because of this integration that the deficiencies of the vestibular system for detecting constant velocity are overcome. Thus, the main point is not that there are multiple sensory inputs for specifying self-motion, but that they must be organized in an integrated fashion. The nature of this integration, e.g., algebraic summation or hierarchical, remains, however, a source of much current speculation (Dichgans & Brandt, 1978; Nashner & McCollum, 1985). The elusive problem for all current models is to explain how postural stability is maintained even though different sensory inputs sometimes provide conflicting information as to whether or not movement is occurring.

Two Modes of Visual Processing

An important implication of the preceding discussion is that the visual system serves two different functions (Schneider, 1967). One is concerned with pattern perception and the recognition of moving objects in the spatial layout (focal vision); the other is concerned with spatial orientation, locomotion, and posture (ambient vision). During most activities, and especially during locomotion, both functions must occur concurrently (Bertenthal & Campos, 1987). How might this occur? A review of the empirical data suggests that the visual system processes information mediating each of the two functions differently (Leibowitz & Post, 1984). Some of the most important distinctions include retinal location, awareness, and adaptation to optical rearrangements.

1. Retinal location. There is considerable evidence that focal and ambient vision are mediated by different retinal distributions of stimulation. Focal vision involves primarily the central visual field where the fine details of an object can be processed. Even though object recognition is possible in the periphery, this function is much more efficiently processed in the central field. In contrast, the ambient system is mediated primarily by information from the seen periphery, both the retinal periphery and the periphery in depth (Dichgans & Brandt, 1978). For example, Brandt, Dichgans, & Koenig (1973) report that stimulating up to 30° of the central

visual field almost never produces a perception of self-motion, whereas the same amount of stimulation in the retinal periphery almost always produces a positive response. Moreover, masking even the central 60° of the central visual field does not impair the perception of self-motion as long as the peripheral visual fields are stimulated.

2. Awareness. Virtually all focal processing occurs under the conscious control of the observer. It is this mode of processing that is necessary for any form of pattern perception or object identification. Conversely, most ambient functions operate without any awareness by the observer and are designed to automatically interact with various motor activities, such as postural stability. It is specifically this ambient process that explains why an individual is able to read a book while walking and still avoid falling down.

3. Adaptation. Focal vision appears much less able to adapt to optical distortions than does ambient vision. Held reports that prismatic distortions involving orientation are readily modifiable through experience but that distortions of shape show long-lasting deficits (Held, 1970). For example, prolonged exposure to optical reversal of the visual field changes the perceived direction of self-motion (Oman et al., 1980). Analogous effects involving a change in the perceived shape of objects are extremely uncommon.

This dissociation between object recognition and spatial orientation is biologically adaptive since it allows observers to effectively explore an environment without needing to relegate much visual processing to their movements. In adult observers, ambient vision is mediated primarily by the periphery, is divorced from awareness, and readily adapts to optical distortions. Focal vision is mediated primarily by visual information located in the center of the visual field, and produced by the movements of other objects. Visual processing generally involves delimited regions of stimulation on the retina, and is subject to awareness and resistant to changes. Thus, there are two different modes of processing involved in the perception of motion that appear to work in parallel, enabling observers to perceive the spatial layout while simultaneously monitoring their own self-movements.

This view of perceiving self-motion raises a number of important developmental questions. Do infants differentiate between retinal stimulation produced by the motion of other objects and that produced by their own movements? When do infants begin to perceive their own movements during locomotion? How does ambient processing change as a function of early locomotor experience? A series of recent experiments examining infants' postural responses to optical flow are beginning to answer these questions.

Developmental Findings on the Perception of Self-Motion

One of the most compelling experimental paradigms for demonstrating that global optical flow is perceived as self-motion was devised by Lishman and Lee (1973). This paradigm involved a "moving room" that corresponded to a large box with one end and the floor removed. The remaining three walls and ceiling were suspended from the real ceiling such that the box could be made to swing back and forth. Even though the floor remained stationary, observers situated in the room showed postural compensations that were consistent with the direction of room movement.

The reasons for these compensations are depicted in Figure 1. As the room moves away from the observer (Panel A), there occurs a global flow of optical texture projected onto the retinas of the observer. The direction of this flow would normally accompany the backward sway of an individual (Panel B). If this optical flow is perceived as self-motion, then the observer will automatically respond with a postural compensation to correct for the perceived backward sway (Panel C). This compensation will cause the observer to sway forward and sometimes lose balance. These responses are especially dramatic because both mechanical and vestibular information initially specify no movement and hence postural stability.

The first research using this paradigm was conducted with adults and it was revealed that subjects standing in the room tended to sway in synchrony with the movements of the room. These findings thus provided convergent support for concluding that visual information about body movement is used for maintaining postural stability. Moreover, the initial posture of the observer was irrelevant to the perception of self-motion. This percept was reported regardless of whether the individual was standing, sitting, or lying down. Most importantly, none of the observers reported that the walls were moving. Instead, they all perceived themselves to be swaying.

Postural Compensations in Standing Infants

The success of this paradigm for testing adults suggested that it might prove useful for testing infants as well, especially since it involved an automatic and nonverbal response. Two early studies using the "moving room" paradigm to assess postural stability by infants were conducted soon after the paradigm was introduced (Lee & Aranson, 1974; Butterworth & Hicks, 1977). In this research, standing or sitting infants between the ages of 11 and 18 months, were placed inside a version of the moving room apparatus and their postural compensations to the displacements of the room were observed. The results were very consistent in revealing directionally appropriate postural compensations to the movements of the room. Still, it was difficult to conclude unequivocally from these findings that infants perceived the global optical flow produced by the movements of the room as self-motion. Conceivably, infants might have shown the appropriate postural responses because of the "looming" of the front wall or because they were simply tracking some of the visible contours.

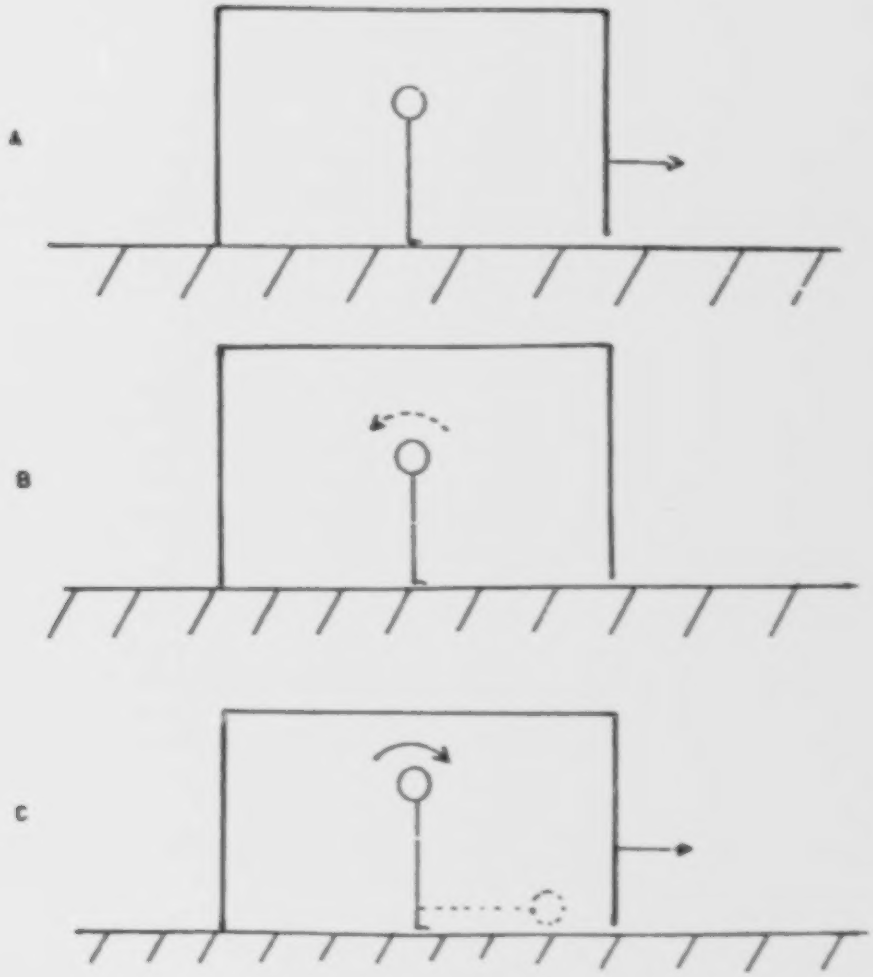
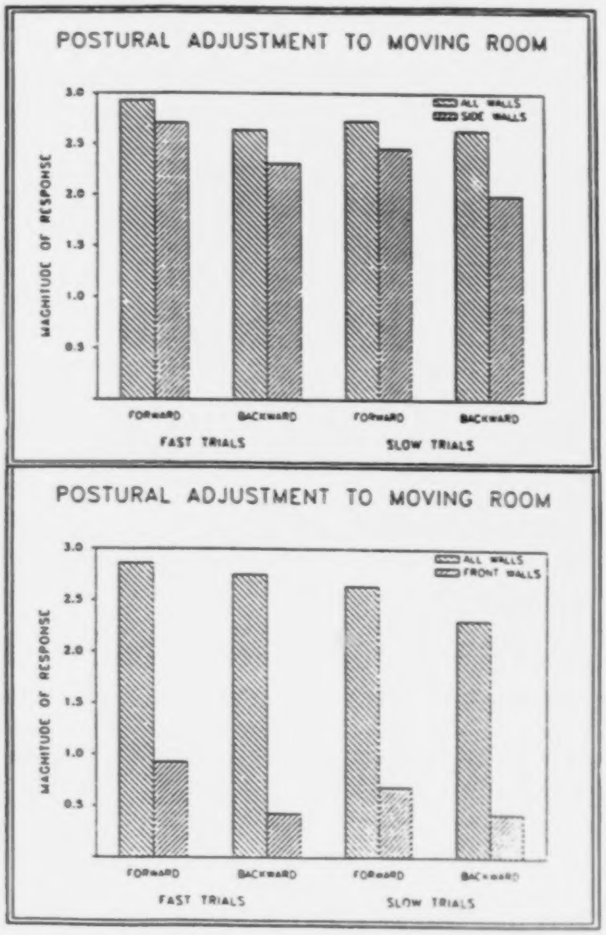


Figure 1. Panel A depicts the room moving away from the observer which produces a global flow of optical texture. The direction of this flow normally accompanies the backward sway of an individual (Panel B). If this optical flow is perceived as self-motion, then the observer will compensate by leaning forward (Panel C). (from Lee and Aronson, 1974).

More recent work on this issue by us discredit this alternative (Bertenthal et al., 1986). It was recalled that in adults, visual stimulation of the retinal periphery is sufficient for producing a postural compensation. If the same is true for infants, then they will show an appropriate postural compensation to peripheral stimulation even when the central visual field remains stationary. As such, this manipulation is useful for eliminating the possibility that infants are simply tracking visible contours in the center of the visual field. More importantly, this manipulation provides an opportunity for testing whether or not the different modes of visual motion processing (object vs. self) are spatially distributed even during infancy.

This initial investigation involved infants between 12 and 15 months of age (mean = 13.9 months), all of whom were capable of standing upright without support. The apparatus was very similar to the version of the "moving room" described by Butterworth and Hicks (1977). In essence, it consisted of a small room (1.2 X 1.2 X 2.1 M), open at one end, and mounted on top of a stationary floor with tracks running along its sides to guide the back and forth movements of the room. The interior of the room (3 walls and ceiling) was lined with a vertically striped green and white pattern (stripes = 3.3 cm). In order to control the direction of the child's visual gaze at the beginning of each trial, a toy animal was placed in a plexiglass box inset into the front wall. This box was illuminated and the toy began moving prior to each trial. In contrast to earlier versions of this room, the front and side walls of the room were uncoupled so that infants could be tested while the whole room moved (global optical flow), only the side walls moved (peripheral optical flow), or only the front wall moved (central optical flow). During the experiment, infants stood inside the room on the stationary floor and faced the front wall. At it furthest distance, the front wall was 104.14 cm from the infant and subtended a visual angle of 48° x 48°, while at its nearest distance the wall was 63.5 cm from the infant and subtended a visual angle of 62° x 62°. Each trial began with a 10 sec. baseline period followed by a movement of the room toward or away from the infant.

Infants were tested in one of two experiments. Experiment 1 involved two conditions: (1) movement of the entire room, and (2) movement of the side walls. Experiment 2 also involved two conditions: (1) movement of the entire room, and (2) movement of the front wall. Within each condition, there were two trials in which the walls moved slowly (10.16 cm/sec) and two trials in which the walls moved fast (20.32 cm/sec). The total distance of the movement was held constant at 40.64 cm. Each condition was further defined by the direction of movement. On two trials the walls moved toward the infant, while on the other two the walls moved away from the infant. Thus each infant received a total of 8 trials blocked by condition and counterbalanced by condition, velocity, and direction.



POSTURAL ADJUSTMENT TO MOVING ROOM

POSTURAL ADJUSTMENT TO MOVING ROOM

Figure 2. Mean postural responses to moving room as a function of condition by 14-month-old infants. Top panel corresponds to Experiment 1; bottom panel corresponds to Experiment 2.

A 4-point rating scale was used for scoring the postural stability of the infants during the movement of the room (0 = no response; 1 = postural sway but no movement of the feet; 2 = stagger - one or more steps - but no fall; 3 = falls to the ground). As can be observed in Figure 2, infants in Experiment 1 showed virtually no difference in responding as a function of whether the whole room moved or only the side walls moved. In contrast, infants in Experiment 2 showed significantly more compensation to the movements of the entire room than to the movements of the front wall. Moreover, a between-subjects comparison between infants' responses to the side walls and to the front wall revealed that their postural compensations were significantly greater to the movement of the side walls.

Taken together, these findings provide compelling evidence that infants, like adults, are sensitive to global and peripheral optical flow for specifying self-motion. Conversely, optical flow in the center of the visual field is not responded to in a like manner, presumably because this stimulation is perceived as object motion. Convergent support for this interpretation comes from assessing the proportion of trials on which postural responses are directionally appropriate. In the whole room and side walls conditions, postural responses were directionally appropriate on over 90% of trials. In the front wall condition, this percentage dropped to approximately 50% which corresponds to chance.

Thus, we conclude that by 12 to 15 months of age the perception of self-motion is already dominated by the retinal periphery. In other words, infants perceived the optical flow as specifying self-motion not only when there occurred global optical flow, but also when there occurred only peripheral optical flow. This latter condition is the most revealing since the center of the visual field remained unchanged, and thus conflicted with the peripheral information. Nevertheless, infants responded to the peripheral information and seemingly disregarded the central visual information (at least as it pertains to self-motion).

The results also suggested that postural compensations were elicited as effectively by peripheral as by global optical flow. This latter finding could be interpreted as supporting the notion that self-motion is processed exclusively by the periphery, but there is a caveat. A majority of infants in the preceding experiment received maximum scores because they often lost their balance and fell. This finding is not surprising given that most of these infants had only a few weeks of walking experience, and thus had little experience in controlling their upright postures. As a consequence, it is necessary to consider the possibility that there was a ceiling effect in the last study which prevented us from observing a difference in infants responding to peripheral and global optical flow. In order to evaluate this possibility more thoroughly, a second experiment was conducted involving 18-month-old infants. It was expected that these infants possessed greater postural stability, and thus were less likely to produce another ceiling effect.

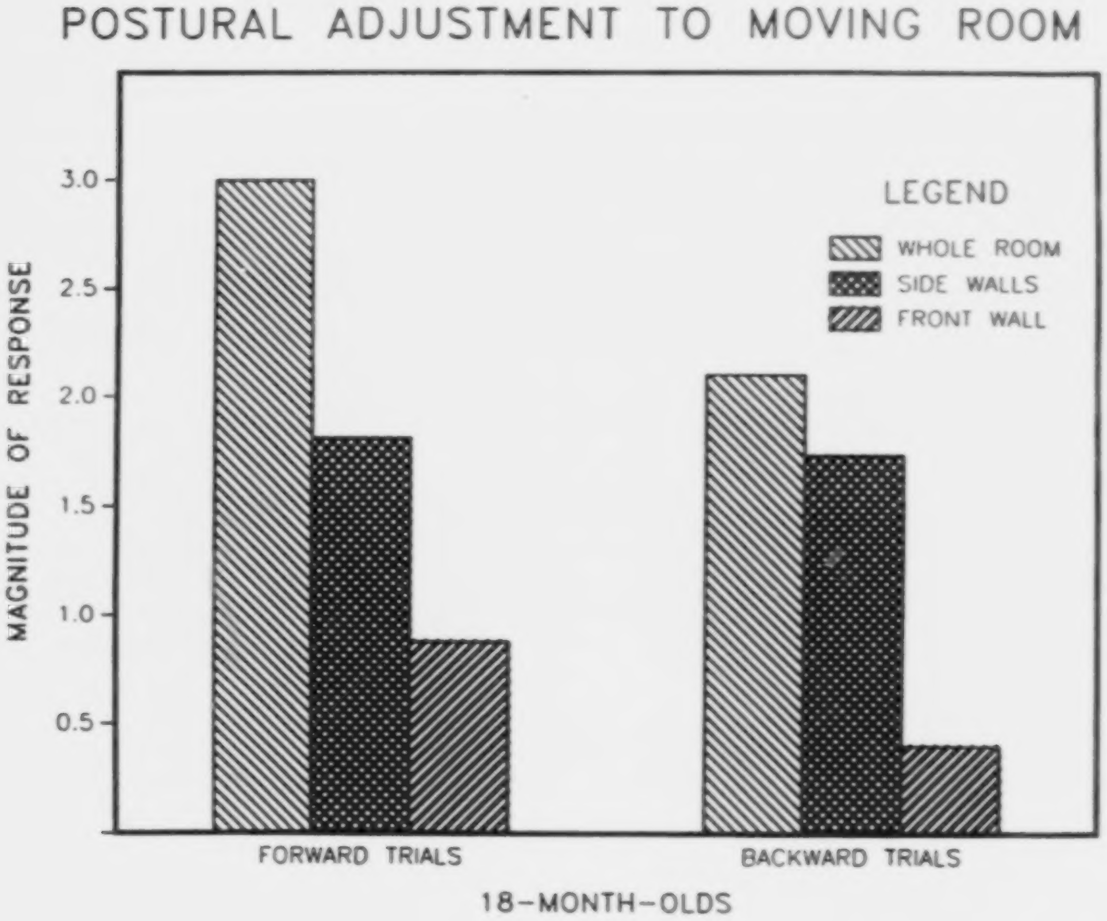


Figure 3. Mean postural responses to moving room as a function of condition by 18-month-old infants.

In this second experiment, a total of 12 18-month-old infants were tested in the moving room. The only procedural difference between this study and the preceding one was that all infants were tested in all three conditions; thus, each infant received a total of 12 trials blocked by the three conditions. As expected, fewer of the infants in this experiment received a maximum score since falling to the ground was much less common. Figure 3 presents the mean performances as a function of condition. Consistent with the findings of the first study, postural adjustments in the whole room and side walls conditions were significantly greater than those shown in the front wall condition. In addition, the comparison between the whole room and side walls condition also showed a significant difference. This latter result thus confirms that there was a ceiling effect that obscured the differences in the first experiment. Apparently, global optical flow is more effective than just peripheral optical flow in producing a postural compensation during the second year of life. But the more important finding is that peripheral stimulation again dominated central stimulation in perceiving self-motion.

Before proceeding, let us consider in more detail why falling should decrease between 14 and 18 months, as these same mechanisms will apply to other developmental changes that we discuss later. As the infant begins to produce a postural compensation to the optical flow, there occurs a postural sway that places the body in disequilibrium with the inertial-gravitational frame of reference specified by the vestibular system. This new vestibular stimulation thus engages a new pattern of movement synergies that is either designed to dampen or reverse the initial postural response. The maintenance of an upright posture is therefore a function of not only detecting the vestibular stimulation rapidly enough, but also correctly organizing the appropriate movement synergies and activating them with sufficiently short latencies. Given the current procedures, it is uncertain whether one or both of these factors are responsible for the improved postural stability.

Regardless of which mechanism represents the rate limiting factor in reducing postural instabilities, it seems reasonable to speculate that experience with controlling upright posture is a contributing factor to the improved sensory-motor coordination that occurs with development. Some modest support for this proposal was provided by the results of the preceding study. If the magnitude of the child's postural responses show some adaptation over the course of the experiment, then it would seem reasonable to conclude that postural responses are modulated through experience. In fact, there was a reduction in postural compensations over the course of the 12 trials. Thus, even though the postural response is controlled by an automatic process, it appears to adapt to the misleading sensory information. Moreover, this conclusion is consistent with the previous discussion concerning the two modes of visual processing where it was pointed out that the ambient system is very sensitive to adaptation effects.

Postural Compensations in Sitting Infants

Taken together, these first two studies revealed that infants by the second year of life perceive large areas of optical texture moving on the retina as specifying self-motion and that this perception is dominated by the retinal periphery. In view of these findings, it seemed quite reasonable to pursue this issue with even younger infants. In order to do so, however, it was necessary to modify the procedure so that infants who could only sit or who could only sit with support could be sensitively assessed (Bertenthal et al., 1987). Our solution was to devise a canvas sling that supported the infant in the middle of a small platform. This platform sits placed on four rubber balloons that are configured in such a way that changes in posture by the infant are reflected in pressure changes by the balloons. These changes are detected by a pressure transducer, and then digitized and sampled by a computer every 0.1 sec. Figure 4 shows an example of the parametric curves created by plotting the changes in pressure from two of the four channels during the trial. These functions are used to compute slopes from the digitized data to characterize pressure changes during a 5 sec. baseline and during the period when the room is moving. A significant difference between these two slopes is interpreted as a directionally appropriate postural response as long as the sign of the difference is consistent with the direction of the moving walls.

In this most recent work, we tested a total of 36 infants at five, seven, or nine months of age. The design was identical to the one used with the 18-month-old infants. Each infant received a total of 12 trials blocked by the three conditions. The results suggested a number of significant changes occurring within this age period. As can be observed in Figure 5, infants at nine months of age showed directionally appropriate postural responses when stimulated with global or peripheral optical flow, but there was no evidence of a postural compensation when optical flow was restricted to the central portion of the visual field. The results for the 7-month-old infants were considerably more modest, yet there was reliable evidence that infants showed postural compensations when the stimulation was global and the room moved forward. (Even though the change in slope was greater for the backward condition, this condition was not significant because the data were much more variable. One interpretation for this increased variability is that an apparent backward sway is less familiar and thus the postural compensation is less systematic.) In contrast, 5-month-old infants showed unsystematic postural responses in each of the three conditions.

It was possible to provide some convergent support for these findings by devising another measure for evaluating postural compensations. The previous measure assumed a linear change in pressure as a function of time. If the actual change was somewhat more complex, it might remain undetected by evaluating only the slope of the parametric curve. As a response to this possibility, the second measure made no assumptions about what function would best describe the change. This measure was operationalized by allowing two independent observers to view the graphs of the pressure changes for each trial and then make a decision as to whether the room was moving toward or away from the infant. Each graph (see Figure

4) displayed two functions depicting the pressure changes of the two most significant channels (one measured pressure changes from the balloon located at the front of the base plate and the second measured pressure changes from the back of the base plate). The beginning and end of the room movement was marked on each graph as well. The advantage of this metric over the preceding one is that the observer could use any portion of the plotted curve to arrive at a decision. Thus, the number of correct judgments by each observer would depend upon the appearance of any systematic differences (and not just linear differences) between the baseline and the movement of the room.

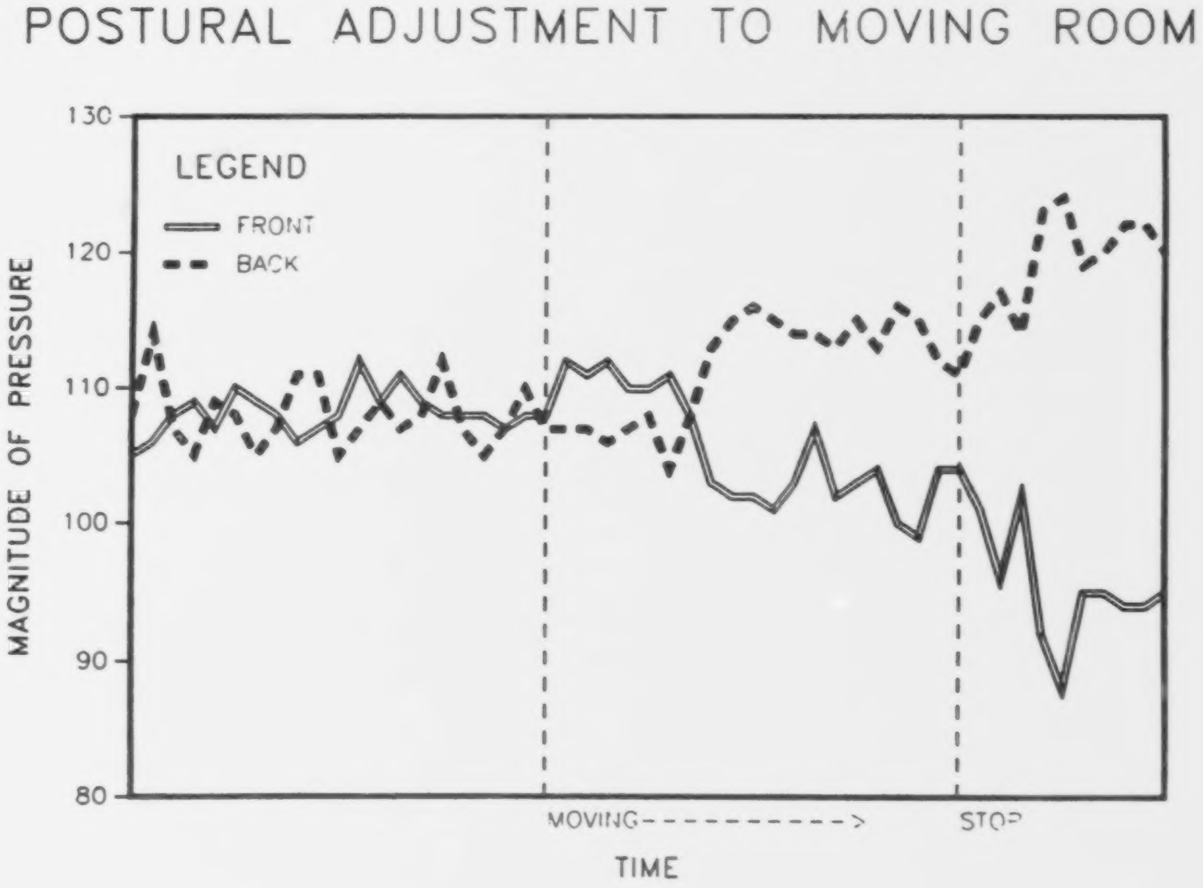


Figure 4. Representative example of the parametric curves created by plotting change in pressure from front and back channels over the course of the trial.

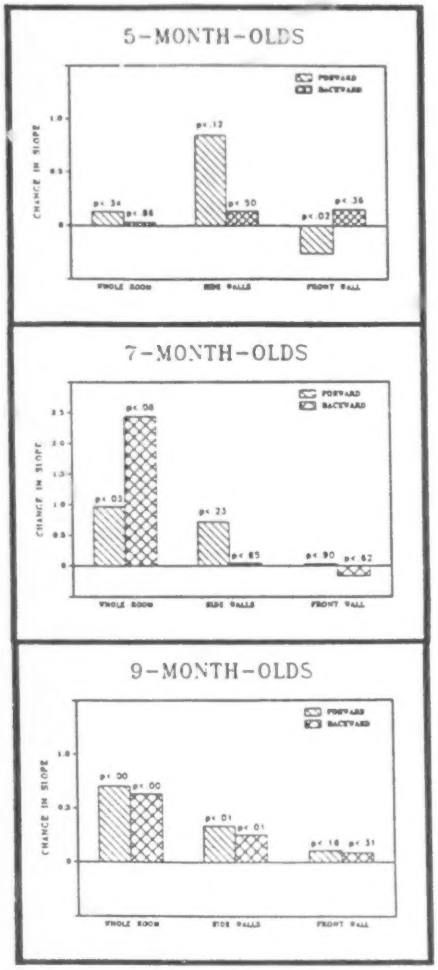


Figure 5. Mean change in postural responding as a function of condition and age.

The responses of the 5-month-old infants were too variable and thus proved unscorable. In regard to the 7- and 9-month-old infants, judgments based upon their postural responses are depicted in Figure 6. As can be observed, the 9-month-old infants showed systematic responses corresponding to the direction of room movement in the whole room and side walls conditions, while the 7-month-old infants were judged correctly for only the whole room condition. (It can also be observed that the 9-month-old infants showed systematic responses to the front wall in the forward condition. Although this finding was not anticipated, it is not difficult to explain given the increased sensitivity of this latter measure. Conceivably, the movement of the front wall toward the infant was momentarily perceived as a looming object which, in turn, produced a brief increase in backward pressure. Although this modest postural response was not detected when integrating changes during the entire period of room movement, it was nevertheless sufficiently consistent to provide both judges with a systematic response.) In general, then, these findings converge with the previous data to reveal that infants begin to show sensitivity to optical flow for specifying self-motion by 7 months of age, and that by 9 months of age it appears that this sensitivity is dominated by the retinal periphery.

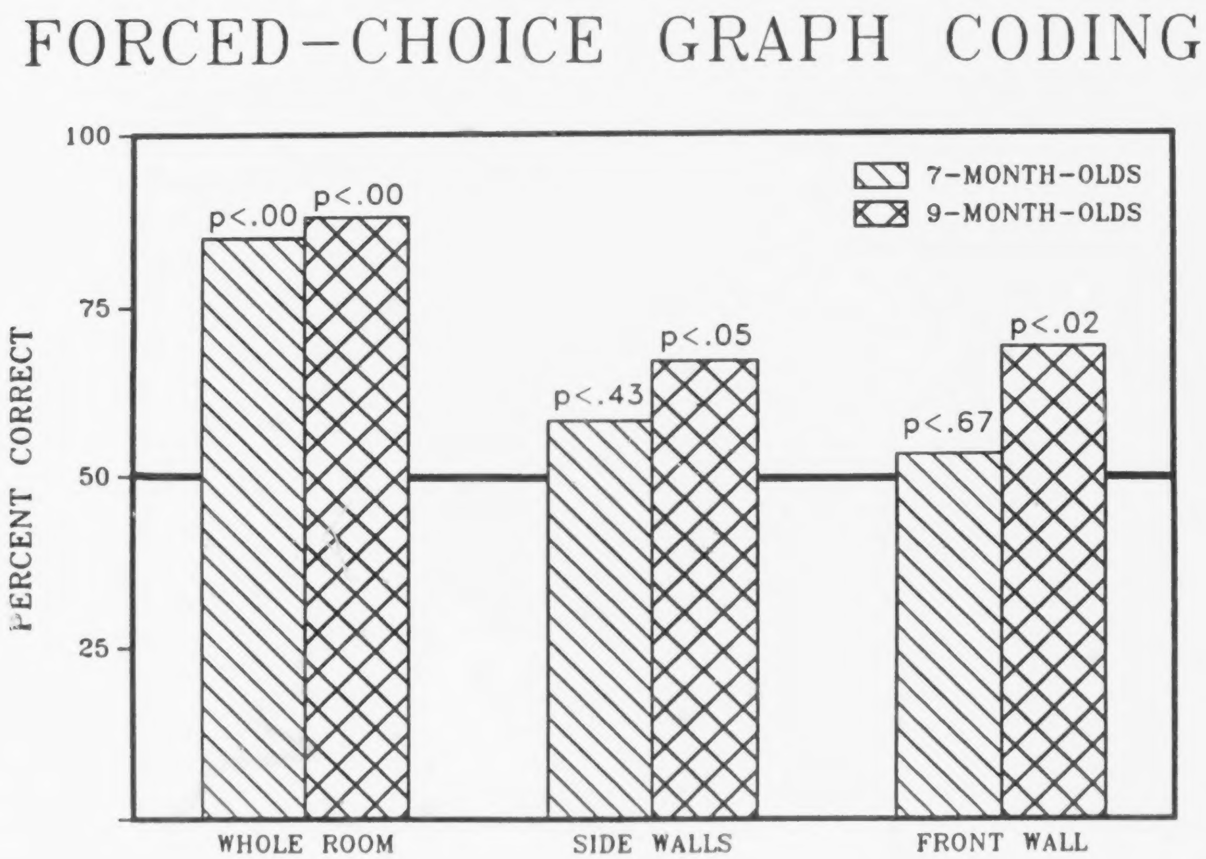


Figure 6. Mean percentage of correct judgments as a function of condition and age.

This last set of findings is especially intriguing. Basically, the data suggest that two significant changes occur in the processing of self-motion between five and nine months of age. The first change occurs between five and seven months of age and corresponds to the time when infants begin to display appropriate postural compensations to global optical flow. One possible interpretation for this shift is that visual and vestibular inputs are not integrated until this age; thus, even if self-motion is perceived, it is not coordinated with an appropriate postural response since these responses are mediated through the vestibular system. Although this possibility appears quite rational, it is inconsistent with a number of studies showing visual-vestibular interactions during the first few months of development (Jouen, 1984). A more compelling possibility is that the rate limiting factor is the necessary muscle coordination for controlling the trunk. The first evidence of this coordination is found with the onset of sitting unsupported and self-produced locomotion which both emerge around seven months of age – the same age that appropriate postural compensations are first observed. Thus, there is a parallel between this developmental shift and the changes observed around 18 months of age. Both changes in postural responding to the sensory inputs emerge with experience in controlling the relevant movement synergies.

The second significant change occurs between seven and nine months of age and reflects a developmental shift toward the sufficiency of peripheral optical flow for specifying self-motion. In view of our previous discussion on the two modes of processing for object and self-motion, we find these results extremely provocative. Recall that the principal reason for the visual system needing two modes of processing was to enable the individual to move through the environment while simultaneously inspecting objects and surfaces. During the first few months of infancy, this form of concurrent processing is less essential since displacements by the infant are restricted to head and trunk movements. Even more importantly, the infant is not able to maintain a stable posture without some external support. Thus, continuous monitoring of self-motion from the optical flow is not necessary since the infant remains supported independent of maintaining a balanced posture. These conditions change dramatically, however, with the development of self-produced locomotion. Not only must infants balance themselves, but they must continuously monitor their own movements since their posture changes from one moment to the next. It would be difficult to imagine how this task could be accomplished without a dissociation between object and self-motion processing. In essence, then, these data are consistent with the view that the new processing demands produced by self-produced locomotion contribute to the increased sensitivity of infants to peripheral optical flow for specifying self-motion. From an epigenetic standpoint, this interpretation is quite rational and has considerable face validity. It will remain the role of future research, however, to empirically test this proposition.

Clinical Implications

By way of summary, our findings to date permit a number of general conclusions: (a) infants by seven months of age show sensitivity to global optical flow for specifying their own self-motions and controlling their posture, (b) peripheral optical flow is sufficient for specifying self-motion and postural stability by nine months of age, and (c) experience with each posture leads to increased stability under conditions of sensory conflict. One implication of these findings is that children who are motorically delayed will also evidence delays in the sensory organization of self-produced movements. A case in point was provided by Butterworth and Cicchetti (1978), who studied a group of motor retarded Down's syndrome infants using the moving room. When the performance of these infants was evaluated relative to a group of normal infants, it was observed that even after equating for standing experience the handicapped infants still showed greater postural instabilities when presented with conflicting sensory information. These results thus suggest that poor muscle tone (hypotonia) is not the only factor responsible for delayed motor development in Down's syndrome infants. Apparently, problems in the organization of sensory information also contribute to the postural instabilities that are observed.

Related research by Nashner, Shumway-Cook, and Marin (1983) suggests that assessing the postural responses of handicapped infants to conflicting sensory information is useful for diagnostic purposes. For example, children with ataxic cerebral palsy are distinguished clinically as showing low muscle tone and a wide based unstable gait. Yet, Nashner et al. tested such a group of children and found that they showed little difficulty in organizing the movements responsible for postural stability under normal sensory conditions, but showed considerable evidence of postural instability when exposed to conflicting sensory information. These findings thus suggest that alterations in gross motor behaviors can sometimes arise from very different mechanisms than those predicted by the clinical literature. From our perspective, the point to emphasize about this example is that a more analytic approach to studying postural stability promises to provide a more complete understanding of the mechanisms directly responsible for the aberrant motor responses.

Finally, it should be obvious from these findings that the relation between self-produced locomotion and the development of visual-vestibular relations is reciprocal. Posture and balance are necessary for independent locomotion, but at the same time, these processes will become increasingly refined through locomotor experience. These developmental changes are fundamental to the acquisition of many later complex motor skills, such as running, jumping, etc. Thus, a more complete understanding of the processes governing postural stability should enable us to better understand the development of skilled activity.

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SPATIAL UNDERSTANDING IN INFANTS WITH MOTOR HANDICAPS

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ABSTRACT

Normal children between six and nine months of age demonstrate a major change in search strategies. This shift from a predominately egocentric strategy to a predominately objective strategy appears to be facilitated by the acquisition of self-produced locomotion. This study was conducted on a group of children with delayed self-produced locomotion to see if the same relationship existed between search strategy and self-produced locomotion. Seven children with myelodysplasia were studied using a spatial reference task developed by Bremner and Bryant. All children were pre-locomotor at the onset of the study. Self-produced locomotion occurred at a mean age of 10.5 months. Prior to self-produced locomotion, independent of age, the infants were successful in their search strategy 15% of the time. Following the acquisition of self-produced locomotion they were successful 72% of the time. This study confirms the relationship between self-produced locomotion and the acquisition of certain cognitive skills. There may be implications for children with motor handicaps.

The data presented in this study are part of a converging research strategy developed to strengthen the premise of the research of Drs. Campos, Bertenthal and collaborators (Bertenthal et al., 1984; Campos & Bertenthal, 1985; Campos et al., 1986). The study extends previous work examining relations between self-produced locomotion and developmental shifts in spatial understanding.

Normal healthy infants between six and nine months of age show major changes in their search strategies. For instance, as has been shown earlier, infants improve their performance on Stage 4 object permanence tasks, showing a new ability to find an object hidden in one of several locations. Likewise, infants shift from a predominantly egocentric (i.e., body-centered) spatial search strategy to a predominantly objective (i.e., landmark-based) strategy. Self-produced locomotion experience appears to facilitate both these spatial cognitive developments. Horobin and Acredolo (1986) suggest that attention is more effectively deployed with acquisition of self-produced locomotion, resulting in less distraction and hence more successful search for objects hidden in one of two locations. Self-produced locomotion can also render egocentric search strategies inefficient. When an infant moves, an object previously to the infant's right can now be anywhere relative to the child's body. By contrast, objects maintain a constant position relative to environmental landmarks. Thus, self-produced locomotion experience should improve performance in search tasks involving spatial rotation.

One question raised by the findings of Campos et al. was whether the same relationships existed in a deprivation paradigm (Bertenthal et al., 1984; Campos & Bertenthal, 1985; Campos et al., 1986). We set out to study the extent to which impediment to self-produced locomotion retards the acquisition of the aforementioned spatial search strategies. If the same relationship were to be held constant, we could then strengthen the argument that self-produced locomotion actually organizes (i.e., changes or influences) perceptual and cognitive processes. The selection of children with myelodysplasia was not made without misgivings. As is well known, children with myelodysplasia present many problems in addition to their locomotor impediments. As Shurtleff (1986) points out in his recent review, attempts to summarize the literature on children with myelodysplasias as to intelligence, visual-perceptual-motor dysfunction, upper extremity function or dysfunction have fallen short, and even descriptive data on the acquisition of non-locomotor milestones are very difficult. Many reports do not distinguish between children with and without complications, with and without hydrocephalus, or with hydrocephalus but without myelodysplasia. Some generalities can be made, at least as they pertain to the Seattle experience.

If one controls for complications of central nervous system bleeding and/or infection, children requiring shunts have a mean IQ below children not requiring shunts - 95 vs. 102 (McLone et al., 1982). Children without hydrocephalus, while in the normal range, tend to cluster at either end of the distribution of normal with more on the lower end (Shurtleff, 1986). The Seattle data confirms this observation. All children with a level of lesion at L-3 or below and without complications were in the normal range on the WISC (Shaffer et al., 1985). There were some interesting and not unexpected verbal/performance discrepancies with verbal scores being higher than performance scores. This discrepancy was more likely to be present in the children who had shunts. The subtests in the normal range were general factual knowledge, vocabulary, logical categorical thinking, social intelligence and visual alertness.

When the WISC scores are divided into the clusters proposed by Kaufman, children with myelodysplasia do best in areas of verbal comprehension and worse in the perceptual organizational abilities and freedom from distraction clusters (Kaufman, 1979). How much of these problems are a function of central processing deficits versus peripheral dysfunctions such as poor eye-hand coordination or motor dysfunction versus deficits in experiences at more critical times in earlier development remains debatable.

The problems of upper extremity dysfunction are thought to be very common and generally significant. Reports on older children using the Jebson-Taylor Hand Function Test indicate that 82% of children with myelodysplasia are below the 2nd percentile (Grimm, 1976). The Seattle data are more encouraging even for children with shunts. When the level of lesion was at L3 or below, only approximately 25% of children were two standard deviations below the mean, and, among those without a shunt, only 2.5% were below two standard deviations. This issue is important to our research since the tasks presented necessitate a guided reach to successfully complete the task. What is not clear is whether the deficits identified using the Jebson-Taylor are present in infancy or are acquired.

Reports on visual dysfunction are varied. Tests using the Frostig Developmental Test of Visual Perception indicate that children with myelodysplasia do poorly; however, other tests such as the Southern California Sensory Integration Test or the Motor Free Visual Perception Test show no systematic differences (Shurtleff, 1986). Among older children, tests using the Berry Test of Visual Motor Integration typically yield below average scores which get worse over time (Shurtleff, 1986). Again, the question unanswered is whether these dysfunctions are present from birth or acquired over time.

The theoretical link between self-produced movement and cognitive development is clearly not all-encompassing but rather specific to spatial understanding and perhaps other areas such as language development and emotional communication. The task before us was to provide convergent validity to the data reported by Campos et al. (Bertenthal et al., 1984; Campos & Bertenthal, 1985; Campos et al., 1986). It was also desirable, and given the subject population, necessary, to demonstrate discriminant validity by testing infants on a skill which is presumably not affected by self-produced locomotion. The test we chose was the Fagan Test of recognition memory. This test served two purposes, the first being a discriminant validity measure and the second being its high predictive validity to later intelligence. The recognition memory test is based on an infant's naturally occurring tendency to look more at a novel stimulus than at a briefly familiarized one (Fagan, 1982). Variations in novelty preference have been shown to be related to later intelligence (Fagan & Singer, 1983). This screening device, when applied to infants, discriminates between infants with normal cognitive development and those without. The test was used to verify that the infants born with myelodysplasia were developing normally in terms of recognition memory, and by inference, in terms of cognition. If, as we suspect, the infants tested appear to be developing normally with respect to this cognitive task, cognitive deficits can be ruled out as a cause of any differences on the experimental task of spatial reference.

One area that is clear is that children with myelodysplasia have delayed motor milestones in infancy (Sousa et al., 1981). In a study of 173 children, the mean age of self-produced locomotion among children with levels of lesion at L3 or below was about 10.5 months. Given all of the aforementioned constraints, we chose to study children with myelodysplasia because if the same relationships that were reported on normal children held true, significant inferences for time specific interventions would result.

The paradigm used was that described earlier by Campos. The apparatus and task consisted in seating the infant in a high chair, mounted on wheels and modified slightly from the normal chair in that a foam rubber shell was inserted to help with trunkal support and allow the child uninhibited use of the upper extremities. The chair was placed before a version of the two position hiding tray devised by Bremner and Bryant 1977). The tray has two submerged wells. Perceptually distinct covers – one white and one black – were used to hide the target object after it was placed in one of the submerged wells. The child was allowed time to become familiar with the object. Then followed a series of tests which the child had to successfully pass on two consecutive trials before the next task was tried. The first was to retrieve a partially hidden object (the so-called Stage 3 task), then to recover the object which was completely hidden in one or the other well. Within a given session the same well was always used; however, wells were randomly determined between sessions. Finally, if the infant was able to successfully complete the single displacement task, the rotation task was tried. In this instance, the object is hidden in the same well as the child successfully found the object but the child is rotated 180 degrees before being allowed to again search for the object. All sessions were video recorded. Each session was scored independently by the tester and by the author. Initial reliability was greater than 80% and the remaining number of trials were discussed until agreement was 100%. A random sample of trials were then scored by Dr. Campos and 100% agreement was achieved.

Nine children were enrolled in the study over a 15 month period. Criteria for entrance into the study included level of lesion L4-5 or below, with or without shunt (as it turned out, all had shunts), no other recognizable syndromes, no history of CNS infections or bleeds and pre-locomotor status at the time of entry into the study. Children born during the study period were enrolled at six months of age. We completed studying seven children. Two subjects did not complete the study; one because of recurrent illness and a second because it became clear over time that additional CNS involvement was present in the form of cerebral palsy. The oldest child entering the study while still pre-locomotor was 13 months. All children were tested monthly until they had completed all tasks and were demonstrating self-produced locomotion. Where possible, Fagan data were collected at 7, 9 and 12 months of age. Four subjects were tested on the Fagan at 7, 9 and 12 months; two at 9 and 12 months, with the 13 month-old being too old to test. Fagan scores averaged 53.8, well within the normal range for age.

All seven children eventually met the criteria for self-produced locomotion, which was the demonstrated ability to move four feet within two minutes with apparent intent. The mean age of acquisition was 10.35 months, with a range from 8.5 to 13.5 months.

The results are summarized in the following graphs. The first figure shows the success rate in mastering the spatial cognition task of uncovering the completely hidden object as a function of age. The percent success rate was 27.3% at 10 months, 72.4% at 11 months and 90.3% at one year of age.

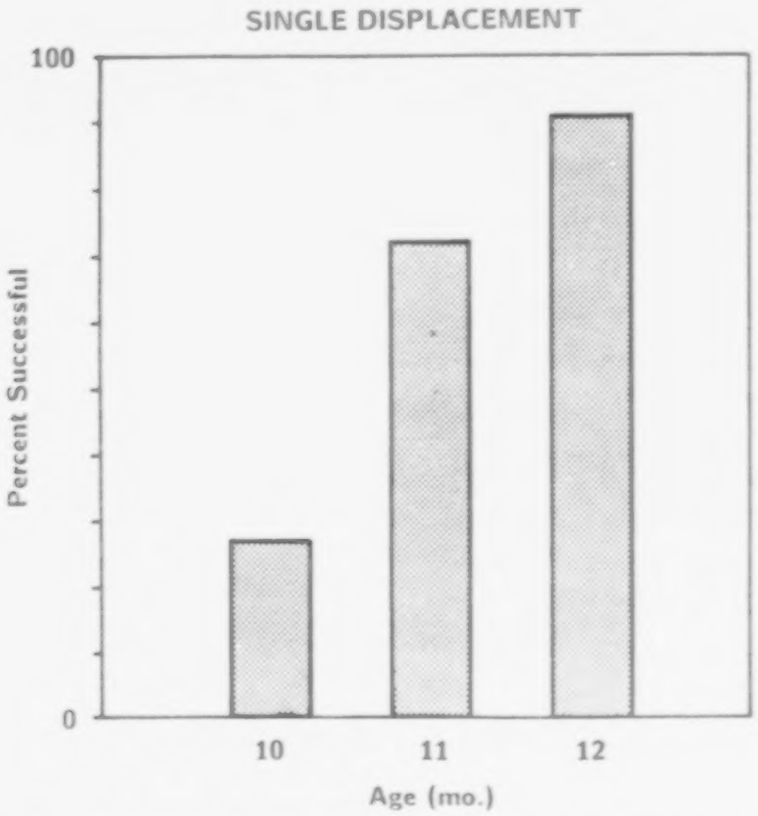

Figure 1. Success rate in mastering the task as a function of age.

The second figure shows the success rate as a function of whether the child was pre or post-locomotor. The pre-locomotor percentage indicates the number of successes in the two months before locomotion, in which there were six successful trials out of a possible 40 for a 15% success rate independent of age. The post-locomotor percent indicates the percent successful for the two months following self-produced locomotion, and in this case there were 54 successful attempts out of 75 for a 72% success rate. In the post locomotor group, the children had been successfully self-locomoting for about two weeks prior to testing.

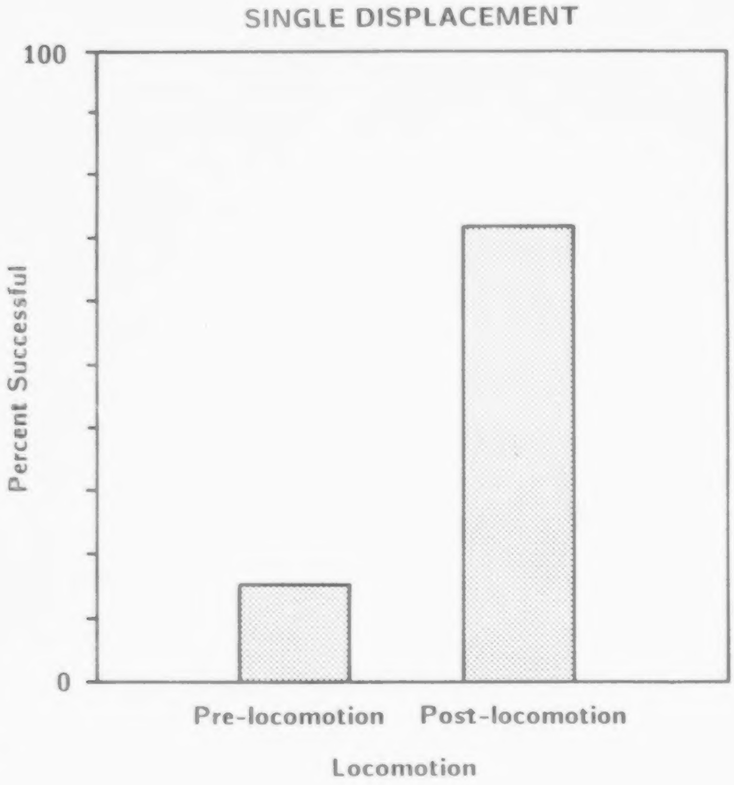

Figure 2. Success rate in mastering the task as a function of locomotor status.

These data provide converging research in support of the position taken by Campos suggesting that the development of self-produced locomotion organizes or facilitates parts of the major developmental reorganization that takes place in normal children at around seven to nine months of age (Bertenthal et al., 1984; Campos & Bertenthal, 1985; Campos et al., 1986; Emde et al., 1976). The results from the children with myelodysplasia demonstrate the same relationship between self-produced locomotion and the ability to successfully complete the task presented.

The ideal comparison group would have been a group of children with clear-cut peripheral handicaps, such as orthopedic problems which required a type of casting that prevented self-produced locomotion for purely peripheral reasons. With current use of orthotics and lightweight materials, it is hard to conceive of a situation in which such children would be found. Obviously inferences are confounded when neurological lesions are related to the motoric difficulty. Even with these concerns, the findings appear robust enough to suggest that the relationship holds in spite of the confounding issues. Even when such confounds exist, however, the identification of islands of retarded psychological functioning, along with the possible prescription of artificial self-produced movement as a therapeutic aid, makes the investigation of such a group clinically and theoretically meaningful.

When considering the importance of self-produced locomotion for children with handicaps, we must be cautious not to make the same mistakes as our predecessors in the 1930s and 40s. Any attempts to relate motor development on a global level to all psychological processes has already been shown to be unsuccessful. Likewise, looking for permanent and immutable effects has been fruitless. This does not mean, however, that motor development at certain critical times does not facilitate or induce specific cognitive functions which might in turn produce differences in outcome in specific areas which have yet to be explored.

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PREDICTORS OF SUCCESSFUL POWERED MOBILITY CONTROL

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Introduction

At present, the provision or denial of powered mobility devices for disabled children or adolescents is governed by many factors, none of which are based upon an objective assessment of prerequisite abilities and skills, or of the person's capacity to learn skills that are necessary for the successful operation of a powered mobility device.

Since the purchase of a powered mobility device with appropriate controls can involve a three to five thousand dollar investment, prescriptions of such devices tend not to be made lightly. Conservative prescription policies are prudent in the absence of reliable predictors of successful wheelchair control. On the other hand, such a policy can potentially lead to more denials of powered mobility than necessary. The denial of powered mobility renders the individual more helpless and less independent but can also cause more subtle long term shortfalls. As Lotto et al. (1983) remark, "[the] effects of motor dysfunction are cumulative and incrementally disabling because motor action and mobility play such a crucial role at every stage and in virtually every aspect of a child's continuing development."

Our experience in the miniature powered vehicle (MPV) project has taught us that a more objective test of actual driving skill is possible and that some of the current prescription criteria are blatantly invalid predictors Lotto et al., 1983). Perhaps the prime example is age, which has long been a criterion for denial of powered mobility (Trefler & Cook, 1980). The MPV project (Lotto, 1983), as well as research by Butler, Okamoto and McKay (1983), Paulsson (1982) and Paulsson and Christoffersen (1984) has shown that children as young as two years of age can learn to safely drive a powered mobility device in a relatively short time (2-12 hours over 1-7 weeks). The children involved in these three projects were all in the average to bright intelligence range. Even the youngest children. including those who at first did not understand the command "go forward," were able to learn to drive the MPV.

Many treatment centers and hospitals throughout North America are developing assessment programs addressing the issue of independent safe powered mobility (Hildreth et al., 1982). At present, it is necessary to purchase at least one electric wheelchair and a myriad of interfaces to have a reasonably complete assessment tool. After the client has been assessed for the appropriate type of interface, he must then be given practical driving experience using the assessment wheelchair before one is prescribed or purchased for him. If a valid computer assessment program was available, it could provide a faster and more objective assessment of a person's ability to operate a powered mobility device safely and independently. This should lead to decreased costs of the assessment program, as there could be a reduced outlay for equipment required and a shorter time required for these assessments.

Relevant Literature

The field of powered mobility is thoroughly under-researched. A literature search is likely to result in five to ten papers that explore technical aspects of wheelchairs (stability, control, propulsion, ergonomics) for every two papers dealing with clinical issues. Of these two clinical papers, one may be empirical (i.e., a report on a study in which an experiment was conducted and data was collected and analyzed), and the other is likely to be an essay or lecture.

It is not as if there are no issues that need to be investigated and no misconceptions that need to be laid to rest – on the contrary. In this context, a review of the empirical literature can be organized around three questions:

(1) What are the effects of the provision of powered mobility on the child and his family?

(2) How can the prescription and assessment for powered mobility be improved?

(3) How can the process of training new drivers be enhanced?

These questions by no means exhaust the list of possible questions; nor do these three questions represent the process of powered mobility prescription and assessment which is presented in detail in the paper by Snell and Balfour (these proceedings, pages 105-116). The questions do provide a framework for the research presented here. The question of the effect of powered mobility is an important empirical one because while few professionals who provide powered mobility devices doubt the benefits of the devices, such evidence is still sparse.

At HMMC a study was conducted in which ten children aged two to five years were provided with a miniature powered vehicle (MPV). Nine children used the MPV at home and/or at school for 14 to 18 months. The Developmental Profile II was used as a pre- and post-test and a number of questionnaires were developed to assess the impact on parents and siblings (Alpern et al., 1980). Table 1 shows the changed scores (in months) of the subscales of the Developmental Profile. The numbers in bold face indicate gains which are larger than the time span of the study and thus larger than scores that would be expected due to the increased chronological age of the children.

This increment was statistically significant ($p < .05$) for the Social and Academic Subscales. Since we were not able to include a control group and in view of the rather small number of subjects, these results should be treated carefully. They do, however, support our intuitions that the provision of mobility has an effect on the social and possibly cognitive development of the driver. Other equally important results show changes in parental attitude away from protectiveness, an increase in the physical activity level of children, diminished stress on the parents (especially the mother), and much anecdotal evidence of increased independence of the MPV driver. One of the measures used in the MPV study was a driving test consisting of five courses that tested driving in a straight line (course 1), S curve (course 2), a left turn (course 3), backing up (course 4), and right turns (course 5) (Figure 1).

Subject #	Time Span	Phys.	Self-Help	Social	Academic	Comm.
1	18	4	-2	**26**	**20**	**22**
2	14	2	0	**16**	14	12
3	18	4	0	16	14	2
4	18	-2	16	**26**	**34**	14
5	18	**26**	**34**	**42**	24	**40**
6	15	8	12	**26**	**24**	10
7	16	6	10	14	10	**20**
8	16	10	18	14	**30**	12
9	14	8	**18**	**32**	**22**	14
10	7	6	-4	**10**	**34**	-6

Table 1: Change scores of Developmental Profile II subscales (in months) between initial and final test (time span = number of months between initial and final tests)

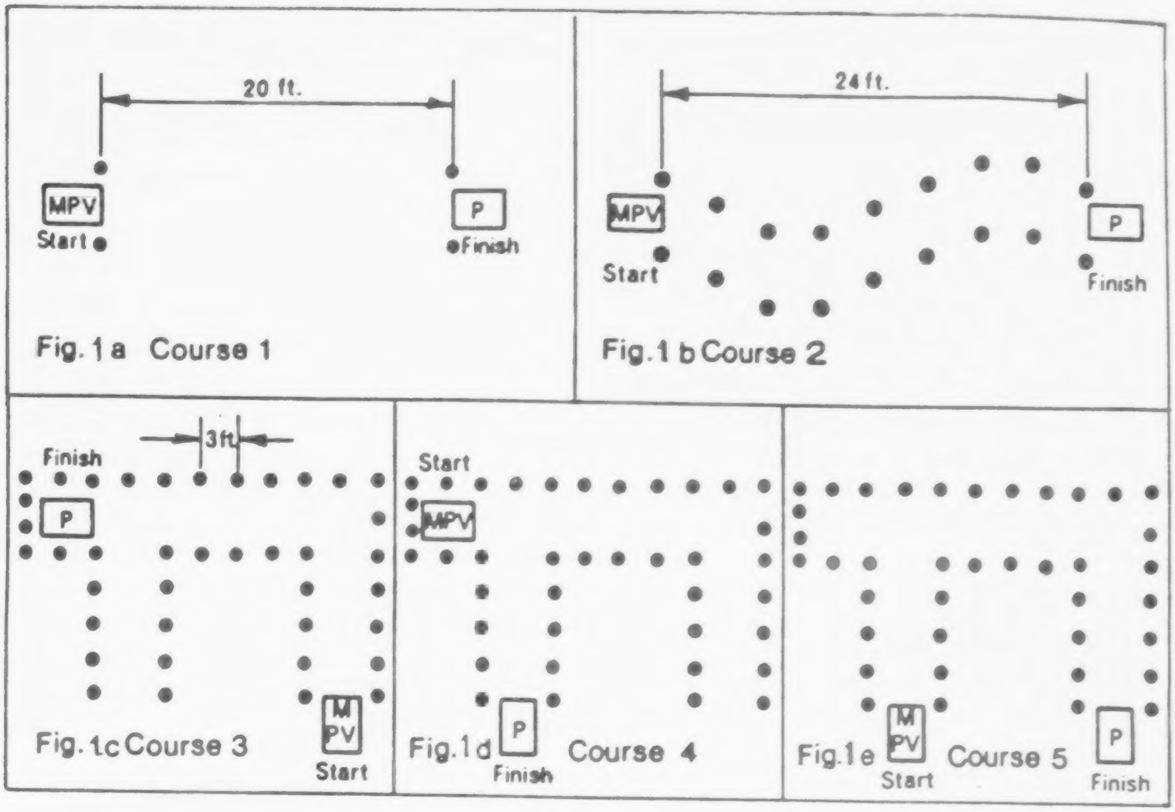
20 ft.
MPV
Start
P
Finish
Fig. 1a Course 1
24 ft.
MPV
Start
P
Finish
Fig. 1b Course 2
Finish
3ft
P
MPV
Start
Fig. 1c Course 3
Start
MPV
P
Finish
Fig. 1d Course 4
MPV
Start
P
Finish
Fig. 1e Course 5

Figure 1: Driving test course.

1a: Driving a straight line
1b: Driving a curved line
1c: Negotiating sharp left turns
1d: Driving backwards
1e: Negotiating sharp right turns

Two studies that have a bearing on prescription and assessment are the research carried out by Sivak and colleagues (1981, 1983) and a simulation project reported by Pronk et al. (1980). Sivak's research will be discussed in the context of the Task Analysis of powered mobility control. Pronk et al. (1980) set out to create a computer program that simulates the behavior of different types of powered wheelchairs. The authors argued that such a simulation program would be efficient since it would allow clinicians to test clients in different (simulated) chairs. This would avoid the need to actually purchase multiple evaluation chairs. Mathematical models were used to simulate the behavior of the different wheelchairs (E & J, Standard, and Newton, Marke). Adult clients controlled the movement of a "house" shaped figure on the computer monitor. Six driving test courses were presented on the monitor. The courses incorporated the actions listed above and added a small and large diameter full circle. Measurements taken were: (1) accuracy (number of course boundary crossings); (2) speed; and (3) number of wrong turns. Pronk et al. (1980) observed that this method of simulated testing holds promise but reported that a number of problems were encountered, i.e.

1) "poor imaginative faculty," (the image appeared to be too abstract for some clients);
2) "poor ability to coordinate movement of the controls with the movement of the figure on the monitor screen;" and
3) "spatial aberrations, manifesting themselves particularly when the subject had to drive 'downwards'" (Pronk et al., p. 134).

These problems are extremely relevant to consider when a computer-based driving simulation program is to be used with children who can be expected to be more concrete, more egocentric (Pronk's problem 3 above), and for whom the temporal or physical distance between cause and effect cannot be very large. A task analysis of wheelchair driving can help to illuminate these points.

Interfacing and types of wheelchair controls almost constitute a field of investigation of their own which cannot be addressed here. I will only mention its importance, as well as that of seating the person, as other areas of research potential.

The analysis that follows will begin at a point at which a subject is seated properly and interfaced with one, two, four, or five switches (i.e., the subject can voluntarily control that number of switches). While much of the analysis will be phrased in terms of joystick movements, its outcome applies equally to any type or combination of switches irrespective of their positions and modes of activation.

Task Analysis of Powered Mobility Driving

Three distinct yet interrelated skill areas necessary for driving control can be identified as:

a) Control of the joystick and its effects;
b) Perceptual skills and visual functioning;
c) Cognitive skills and knowledge of "rules of the road."

The latter skill areas contain the (car) driving instructor's IPDE algorithm for solving problems encountered during driving: Identification of a problem or potential danger; Prediction of the anticipated course of events and planning of alternate actions; Decision regarding which course of action to follow; and Execution of the action.

It is obvious that the three areas of control, perceptual, and cognitive skills are not independent; however, for the purpose of identifying skills that predict driving success, separation of factors is necessary.

Control of the Mobility Interface

The first step toward successful control of an interface is the child's ability to comprehend the cause-effect relation that exists between activation of the switch and the effect produced by this activation.

Brinker and Lewis (1982) presented a developmental hierarchy of the child's understanding of cause-effect relations based on Piaget's theory (1952). Stated from the child's point of view, this hierarchy is as follows:

1) I can make things happen (but I don't know how I did it) – Primary Circular Reaction;
2) I can make this response to make this event happen – Secondary Circular Reaction;
3) This response and other responses can make a variety of different things happen – Elaboration of Secondary Circular Reactions;
4) These responses are tools for finding out what will happen – Coordination of Secondary Circular Reactions and their application to new situations;
5) Different combinations of responses lead to different kinds of information – Means-End reasoning. (Brinker and Lewis, 1982, p. 164).

When the child reaches the fifth step in this hierarchy, he is capable of gaining new information and has learned the fundamental facts that (a) the majority of things happen for a reason, and (b) the child himself has control over events in his world.

For the purpose of driving, control step 2 of this developmental hierarchy may already be sufficient as a starting point. But it is likely that only at step 3, when the child realizes that different actions have systematically different consequences, does the use of a four or eight position joystick become possible.

Thus, attainment of step 3 of the Brinker and Lewis hierarchy can be adopted as a potential minimum level of control for the purpose of powered mobility. In this study, the child's assessment will therefore begin at this level using a microcomputer-based task and simpler toy activation games.

Two other aspects of control, beyond the level of response contingency comprehension, must be addressed. The first of these concerns levels of functioning or levels of complexity of effects, and the second deals with the child's involvement in the movement.

The complexity of the consequence of a switch activation can conveniently be ordered along a continuum of dimensions of control. At the first level are zero-dimensional consequences such as the on/off switch function of a binary switch (e.g., light switch, on/off switch of TV, radio, or a power on/off switch). One-dimensional control is characterized by a linear range of effects; for example, a two-position joystick which allows for forward and backward (or up/down) movement or one that affords left/right movement. Other examples of one-dimensional control are volume and brightness switches (increase/decrease). The complexity that is required for wheelchair control is two-dimensional because the child must be capable of controlling both forward and backward and the orthogonal, left and right movements. A child who performs at the level of step 3 of Brinker and Lewis's cause-effect hierarchy and is capable of operating two dimensional control functions can potentially operate a powered wheelchair.

There is one other aspect of control that must be assessed, which aspect centers around the Piagetian concept of egocentrism and its implication for a child's conception of space and his understanding of spatial relation from his own and others' point of view (Piaget & Inhelder, 1956; Flavell et al., 1978; Rosser, 1983). This egocentrism and the degree of decentration attained by the child can be tested by the four movement control scenarios discussed below.

Egocentrism is variously defined as the child's inability to take another person's perspective or as an excessive reliance on one's own perspective (Shantz & Watson, 1971). Decentration represents the child's increasing ability to take a different perspective both literally and figuratively; different, that is, from his own. To the extent that wheelchair driving requires negotiating one's way through pedestrian or wheelchair traffic, it calls for a driver's ability to anticipate other peoples' movements and directions or change of direction (Bardach, 1971). Also, since decentered stages of development are more advanced than their egocentric counterparts, it is likely that the quality of wheelchair control depends upon the level of decentration of the child.

Four modalities of movement can be postulated, each successive one being more decentered. The first of these is that of driving a powered mobility device (I), which, although not the most egocentric form of mobility, is still fully egocentric. In this modality, activating "forward" will move the child forward; activating the left switch turns the child left and so on. Here the child is egocentrically involved in the movement.

A more decentered modality of movement (II) is one in which the child controls the movement of a toy truck which is remotely controlled via the wheelchair's joystick. In this modality the child controls the movement but is not personally involved. The truck is concretely present in proximity to the child and the child can, as it were, take the perspective of the truck to decide which move to make next.

Studies have been conducted in which children controlled the movement of a floor turtle. This is a turtle-shaped device whose movements are controlled by commands entered on a computer keyboard and relayed to the device. In these studies children were observed to stand up from the keyboard, face in the direction of the turtle and decide whether the turtle should go left or right (Simon, 1983).

A third modality of movement (III) is one in which the egocentric perspective is simulated on a computer screen in a three-dimensional (3D) driving simulation. The child remains immobile but a forward activation will have the appearance of forward motion and similar consequence follow the other switch activations.

Finally, an even more decentered modality of movement (IV) consists of a two-dimensional (2D) simulation of a screen drawn cursor. In this modality the moving object and the course are abstract two-dimensional representations which require the child to understand that he controls one of these represented elements and calls for a decentered perspective.

The hierarchical order of these four driving modalities (I-IV) as listed above is hypothetical. A comparison of all four modalities has not been performed. Modalities II and IV have been used simultaneously in the context of Logo research, but a strict comparison of a child's performance in each modality was not carried out (Simon, 1983; Solomon, 1982). In a pilot study conducted at HMMC, five subjects engaged in the Miniature Powered Vehicle project were asked to perform the identical driving course in modalities I and IV. While all children could perform modality I tasks, the younger subjects (2 yrs - 3 yrs 5 months) could not complete the two dimensional simulation.

Perceptual and Cognitive Factors

In the absence of data on minimum perceptual and cognitive prerequisites of safe and proficient powered wheelchair driving, a task analysis of these skills must be based on other sources. Two such sources are current practice and experience (e.g., licensing practices in the field of automobile driving), and an examination of the records of patients who turned out to be unsuccessful or successful wheelchair or car drivers.

Legal Limits

While the legal minimal visual acuity of at least 20/40 vision exists as a criterion for licensing of car drivers, it is doubtful whether such a strict cut-off is required for the successful control of powered wheelchairs. On the other hand, drivers are not normally tested for visual field defects, and other visual functions (scanning, tracking, memory) which cannot be assumed to be unimpaired in subjects with neuromuscular disorders. There exist no explicit legal limits regarding a person's cognitive ability.

Driver Education Program

In the HMMC Driver Assessment, and Driver Education and Re-Education programs which started as a pilot project in April 1976, approximately 25-30 clients are seen per month for driving assessment and (re)education.

Experience derived from these programs at HMMC and elsewhere has indicated a multiplicity and great variety of perceptual and cognitive limitations consequent to congenital brain damage or (acquired) brain injury. Bleiberg identifies two broad classes of factors:

1) "Abilities necessary to drive"; and
2) "Behavior characteristics that increase the likelihood of having accidents" (Bleiberg, 1981, p.10).

This project assesses the first of these classes of factors. Information about the second class of patient characteristics is more reliably attained in psychiatric or psychological interviews.

Both Bleiberg (1981) and Ranka (1981) point out that standardized tests of perception are too static and fail to assess relevant driving skills. A three-dimensional dynamic simulation is suggested as an alternative.

The information obtained from records does not provide a clear picture of specific deficits that predict success or failure of wheelchair driving beyond the obvious correlations between localized brain damage/injury in right or left hemispheres and the resulting performance problems on the contralateral side.

Task Analysis of Visual, Perceptual and Cognitive Skills

Since it is not possible, on the basis of existing knowledge, data, and experience, to specify an exact minimum level of visual acuity, this measure will be obtained and included in the analysis both in a prediction and in an exploratory capacity.

Visual scanning, visual tracking, visual organization and visual memory are functional skills required for driving: scanning, to check for a free path and to identify potential path infringements; tracking, to assess clearance from and trajectories of other moving objects; organization, to plan, coordinate, and predict the environment and one's movements; and visual memory, to build perceptual schemes and internal representations that afford learning and a degree of automatization of driving behavior.

Whether field of vision defects are potential indicators of driving failure depends on the magnitude of the defect and on the extent to which a patient has learned to compensate for the defect. Thus, defects of the field of vision cannot be used as an exclusion criterion.

Many of these perceptual skills have a large cognitive component, and a test of these skills also measures cognitive ability. This also applies to such skills as estimation of distance, anticipation of danger and even reaction time.

Intuitively, one would expect there to be a level of cognitive functioning below which control of a powered wheelchair becomes impossible. This lowest level may correspond to step 1 or 2 in the hierarchy of Brinker and Lewis (1982).

Predictors of Driving Performance

The only systematic study investigating the relation between perceptual and cognitive skills and car driving in handicapped subjects, to our knowledge, is by Sivak, Olson, Kewman, Won, and Henson (1981). These authors compared 12 measures of perceptual and cognitive skills with both driving performance in a five-course driving test in a parking lot (closed-course) and with in-traffic driving. Three subject groups were employed: 23 brain-damaged subjects (with diagnoses of stroke {13}, traumatic head injury {7} and cerebral palsy {3}), 8 orthopedically handicapped subjects, and 10 able-bodied subjects.

Although Sivak and colleagues studied car driving performance and not wheelchair driving performance, the results of this study will be used as a guide to select perceptual and cognitive predictors. These results are presented in three points below:

1) No significant relationship was found between the demographic variables of age, sex, current student status, years of education, hand preference, total months of driving experience, months of driving prior to and since injury, and elapsed months since injury, and a variable called Composite Driving Index (CDI). CDI is an overall measure of success of in-traffic driving.
2) Brain-damaged subjects performed significantly poorer on all measures than spinal cord-injured and non-handicapped subjects, and no difference between the latter groups was found.
3) Different perceptual and cognitive tests showed significant correlations with CDI index of driving performance for brain-damaged and non-brain-damaged subjects. For persons with brain damage, two subtests from the Wechsler Adult Intelligence Scale (Wechsler, 1955), Picture Completion and Picture Arrangement correlated 0.72 and 0.46 respectively with the CDI index as did the measure of stereo depth (r=0.52).

> Significant correlations for subjects without brain damage (i.e., able-bodied and spinal cord injury subjects) were found to exist between the CDI and Porteus Maze Test (r = 0.77), unsigned error scores of the Rod-and Frame test (r = -0.62), the Abstract Reasoning subtest of the Differential Aptitude Tests (r = 0.55), and the time- adjusted scores of the Ayres Space Visualization Test (r = 0.52).

In a more recent exploratory study, Sivak, Hill and Olson administered 19 microcomputer-based perceptual and cognitive retraining tasks to four subjects (Sivak et al., 1983; Bracy, 1982; Ginautsos & Klitzner, 1981). The authors found some improvement on standardized perceptual and cognitive tests, presumably as a consequence of the microcomputer-based training, and suggest that computer-based tasks which are designed explicitly for training of driving-related perceptual and cognitive skills may benefit brain-damaged persons.

The Question

The question addressed in this project is: What are predictors of successful powered mobility control? A battery of standard perceptual, spatial, motor and cognitive tests was constructed and a number of computer-based tests and driving simulations were developed. The driving tests (Figure 1) were improved by replacing the original bowling pin course markers with orange pylons connected by a plastic ribbon. A radio-controlled vehicle (jeep) was built which operated exactly like a wheelchair in that propulsion and direction changes were controlled by independent motors at the rear wheels.

Methods and Procedures

Subjects

Fifty-seven subjects participated in the study. Twenty-four able-bodied subjects and 33 disabled students were drawn from two neighboring schools, an integrated day care center, and from a treatment center. All students were between four and nine years old and were grouped by age (4-5, 6-7, and 8-9 year olds), disability and powered mobility experience. Seventeen disabled students were experienced powered mobility drivers and sixteen had no experience with powered chairs.

Table 2 presents the distribution of students across these groups.

	Age Group 1	 2	 3
Able-bodied	n = 8 mn = 4.7 sd = 0.62	n = 8 mn = 6.9 sd = 0.31	n = 8 mn = 8.9 sd = 0.24
Disabled, Inexperienced	n = 6 mn = 4.3 sd = 0.27	n = 6 mn = 6.9 sd = 0.60	n = 4 mn = 8.6 sd = 0.39
Disabled, Experienced	n = 5 mn = 5.1 sd = 0.72	n = 6 mn = 7.2 sd = 0.53	n = 6 mn = 9.0 sd = 0.51

Table 2: Number of subjects (n), mean age (mn) and standard deviation (sd) in age, ability and experience groups.

The diagnoses of the disabled students are tabulated below (Table 3). Students with head injuries were excluded from this study since Sivak et al. (1981) found differences between predictors for head-injured patients and persons with cerebral palsy or spinal cord related diagnoses.

	Inexperienced Drivers	Experienced Drivers
Age Group 1 4-5 yr. olds	Cerebral palsy (3) Spina bifida (3)	Cerebral palsy (2) Spina Bifida (1) Spinal muscular atrophy (1) Congenital amputee (1)
Age Group 2 6-7 yr. olds	Cerebral palsy (5) Spina bifida (1)	Cerebral palsy (5) Spinal muscular atrophy (1)
Age Group 3 8-9 yr. olds	Cerebral palsy (4)	Cerebral palsy (6)

Table 3: Distribution of Diagnoses Across Groups

In the course of the data analysis, it became evident that the disabled students were extremely nonhomogeneous in their performance. Two further subdescriptions were made, one based on the student's level of physical functioning and another based on his current method of mobility. The variable of physical ability level consisted of four categories:

1. NW: non-walkers; students who had never walked with or without assistive devices or walkers.
2. SW: students who have had some walking experience in clinics or treatment programs. These students do not walk but have done so at least once.
3. WA: students who walk or have walked independently or with assistive devices. Some of these students may use manual wheelchairs for mobility.
4. RU: able-bodied students.

The mobility variable had five categories:

1. PM: passive mobility. Students are wheeled by caregivers or staff.
2. EW: electric wheelchair
3. MA: manual wheelchair
4. NO: no wheelchair
5. FE: able-bodied

Tables 4 and 5 reflect the distribution of students by age group across the categories of these variables.

	Age Group		
Physical Ability	1	2	3
RU	8	8	8
WA	5	5	0
SW	3	2	4
NW	3	5	6

Table 4: Number of students by physical ability level and age group

	Age Group		
Mobility	1	2	3
FE	8	8	8
NO	5	5	0
MA	2	2	3
EW	4	5	4
PM	0	0	3

Table 5: Number of students by mobility and age group

Both standardized manual and computerized assessment methods were used. The subjects in the experimental group and the experienced drivers' group had some degree of upper extremity dysfunction, particularly with fine manipulative skills. Therefore, to ensure valid cognitive and perceptual test results, the standardized tests chosen did not have subtests that require complex motor responses. The tests also included subtests requiring simple or non-verbal responses, as some of the subjects were non-speaking.

Perceptual Tasks

The tests administered were:

- Motor-Free Visual Perception Test to measure spatial relation, visual closure, figure ground, visual discrimination, and visual memory Colarusso & Hammill, 1972).
- Space Visualization Test to measure spatial relationships (Ayres, 1962).

Cognitive Tests

A trained psychologist/psychometrist administered:

- Colored Progressive Matrices to test general intelligence by means of a spatially loaded measure (Raven, 1965).
- Picture Completion, a subtest of the Revised Wechsler Intelligence Scale for Children (WISC-R), to measure perceptual discrimination and the ability to identify missing elements in sketched figures (Wechsler, 1974).
- Picture Arrangement, a subtest of the WISC-R, to measure cognitive organization (Wecshler, 1974).
- Mazes, a subtest of the Wechsler Preschool and Primary Scale of Intelligence (WPPSI), a test of ability to follow a maze (Wechsler, 1967).
- Representative Stencil Design Test, a spatial and non-verbal test of logical thinking (Feuerstein, 1972).

All tests were administered and scored according to established standard procedures.

Pre-Driving Tasks

Four computer-based pre-driving tasks were developed and administered:

Bird 1: a targeting task in which the student used the joystick or capacitive touchplate switches to guide a dot (bird) on the periphery of the monitor screen into a square (nest) at the center of the screen.

Eight trials (one dot from each cardinal direction plus four diagonal dots) were given to each student. Brief musical feedback followed the successful completion of each trial. Figure 2 shows the screen image for Bird 1.

Bird 2: a tracking task in which students were to guide the dot into the square. Once the dot was inside, the square started to move along the invisible trajectory of the courses of Figure 1. Students were asked to follow the square. The square stopped moving when the dot fell or was accidentally moved out of the square. Upon reaching the end of each course, musical feedback was given and the square moved to the next starting position. Control for this task was egocentric in that the cursor (dot) moved in the direction in which the joystick was displaced.

Collision: a dynamic perception task in which students moved a computer-simulated car image along a straight road (zero-dimensional control; stop or go) and were asked to reach the end of the road as quickly as possible while avoiding stars shooting across the screen from left and right. Three trials with a total of 12 stars at three angles of incidence (horizontal, top-down and bottom-up diagonal) were administered. The stars were released such that four will hit unless the student stops (hit stars), four will pass in front even if the student keeps going forward (lead star) and four would pass behind (lag stars) unless the student stops. An example of the Collision task screen image is presented in Figure 3.

Square: a rectangular maze through which the student moved a car image. Three trials were given. This task was the first one in which a conflict between an egocentric and non-egocentric perspective occurred. When the car was faced down on the screen, a left turn of the car required that the joystick be moved to the right. Figure 4 shows the screen of the Square pre-driving task.

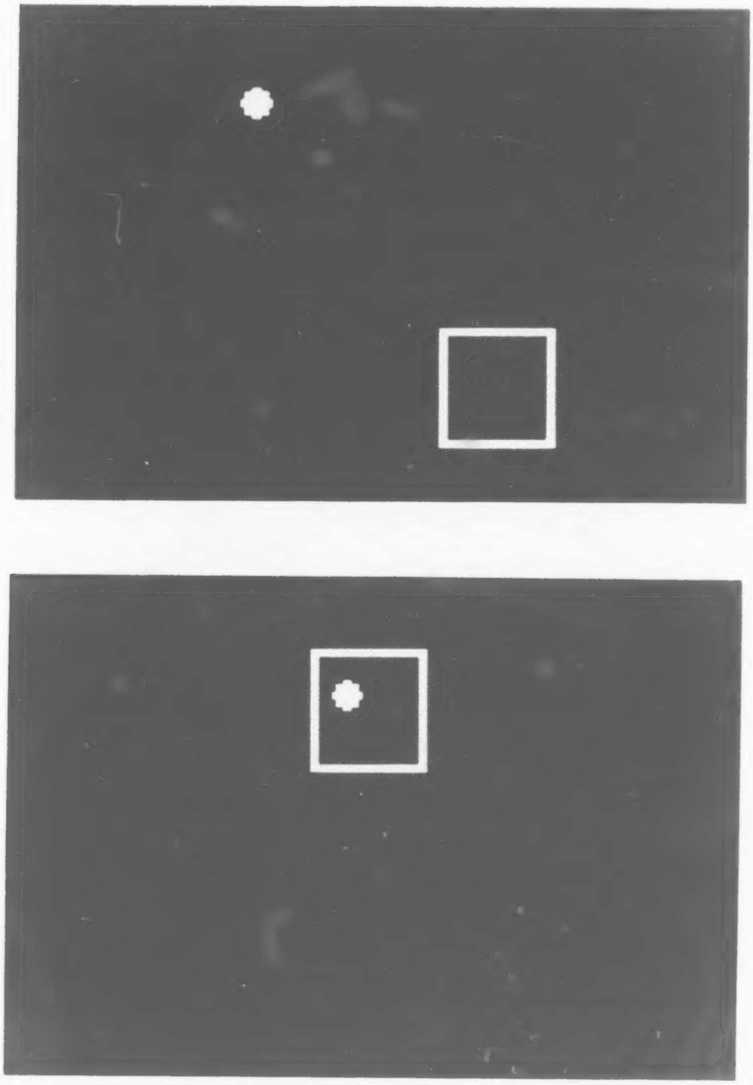

Figure 2: Screen image of Bird 1 (upper panel) and Bird 2 (lower panel)

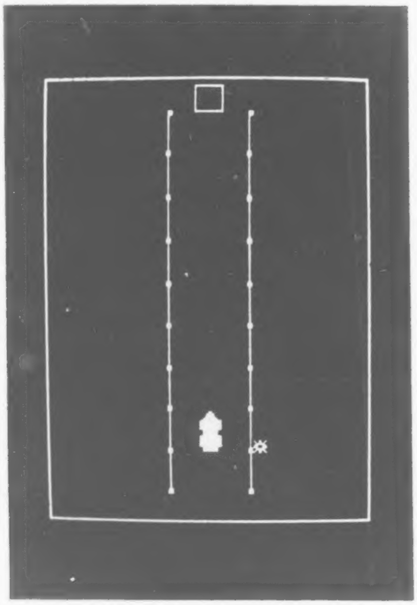

Figure 3: Screen image of Collision pre-driving task

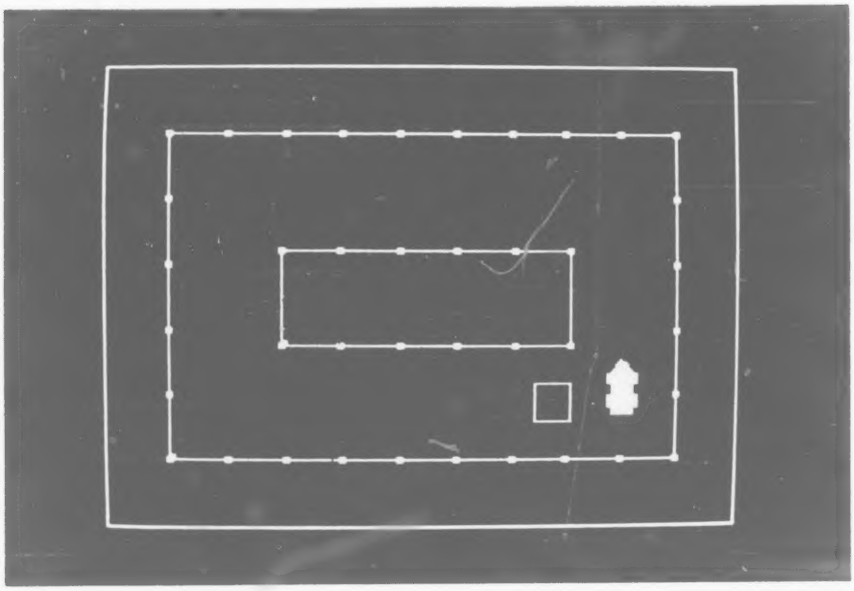

Figure 4: Screen image of Square pre-driving task

Driving Tasks

Five driving tasks were administered: a wheelchair driving task at low and high speed (WLO, WHI); a task in which students controlled the movement of a 12 x 6 inch vehicle or jeep (JP); and two computer simulations of a three-dimensional (3D) and two-dimensional (2D) driving test. All driving tests consisted of the five courses shown in Figure 1. Course size was scaled down to the dimensions of the vehicle or cursor and speed of movement was adjusted to closely approximate the time it took to drive a wheelchair with average load through each course at low speed and a high speed. For the jeep, 2D, and 3D tasks, only one speed could be implemented or proved practical. The jeep had to be driven at high speed because at low speed its maneuverability was diminished. The 2D simulation operated only at the low speed equivalent because the operating system of the Apple IIe computer could not process the computations and display updates and data recordings required of high speed 2D simulation. The 3D program could be operated in both high and low speed but at low speed the image changes on the screen became difficult to notice, causing students to pause, check or alter the joystick direction and collide or give up. Therefore, only data from the high speed version of the 3D simulation were used for analysis. Figures 5 and 6 give examples of the 3D and 2D screen images.

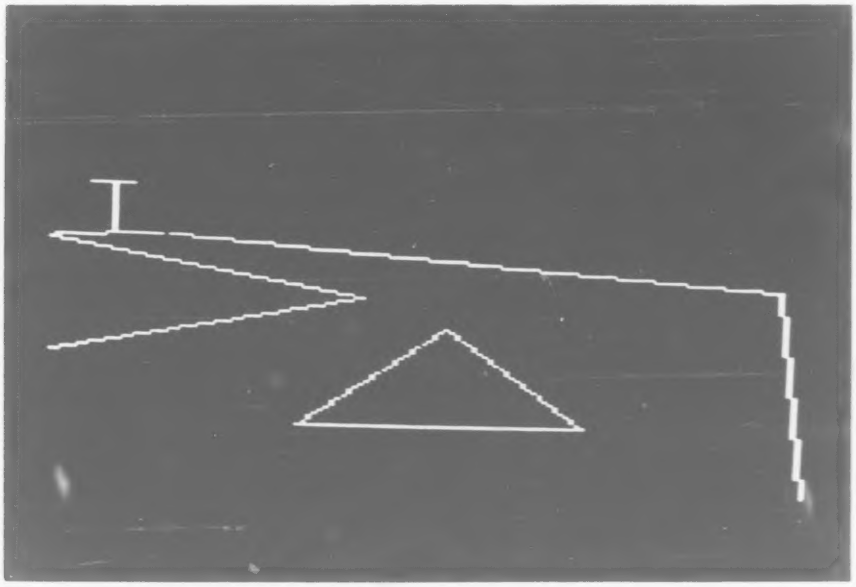

Figure 5: Example of screen image of 3D driving task (Course 2)

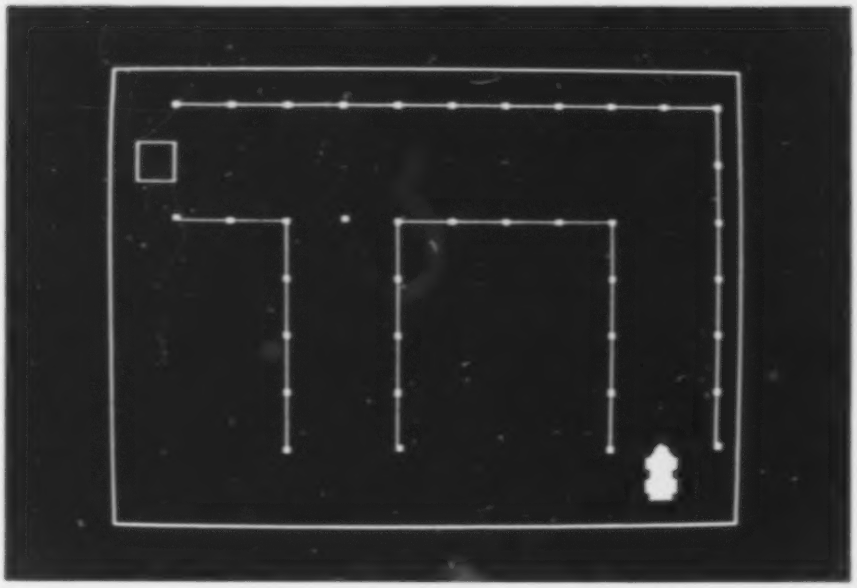

Figure 6: Example of screen image of 2D driving task (Course 3)

Procedure

Standard administration and scoring procedures were used for the perceptual and cognitive tests. The pre-driving tests preceded the driving tests. The order of administration of 2D and 3D tasks was alternated between students. All students received instruction about the joystick or touch plate interface and were allowed to explore the wheelchair, jeep and driving simulations until they could start, stop, and turn left and right upon request. Tests were administered in a quiet room in the school or gymnasium.

Equipment

Simulations and pre-driving tasks were programmed on the Apple IIe in Pascal. A Fortress Scientific wheelchair was used for the wheelchair driving test. The jeep was built with commercially available components, with its control system developed by technologists at HMMC. A commercially available radio transmitter was used to control the jeep and to record the joystick (or touchplate) activations during the jeep and wheelchair driving tests.

Measurements for all computer based tests including wheelchair and jeep tests were stored on individualized data diskettes. Results from the perceptual and cognitive battery were entered in the database. The data were transferred from an Apple IIe to an IBM XT for analysis with SYSTAT (Systat.Inc).

Results

This section presents a preliminary report on parts of the data analysis carried out to date and will focus on one perceptual measure, two cognitive measures (one verbal and two spatial), and on the five driving tasks (WLO and WHI, JP, 2D, and 3D). The driving tests measure that is used is the total number of paddle reads (PR); i.e., the number of times the program read and recorded data input between start and finish of a given course. All joystick activations and non-activations, as well as collisions, were recorded in this way and stored. The PR-variable correlates between .94 and .98 with the time to complete the course and is probably more reliable than the actual time measures, which were recorded with a stopwatch.

Qualitative Comparisons of Driving Test Courses

Able-Bodied Students

In the figures that follow, all disabled subjects are treated as one group (n=33) unless otherwise specified. Two questions needed to be answered first: (1) are these different driving tests comparable?; and (2) what are the differences between the able-bodied and disabled students? Figures 7 through 11 show graphed results for the five driving tests for able-bodied (upper panel) and disabled students (lower panel). In reading these figures, it should be kept in mind that the higher mean PR scores correspond to higher mean completion times and thus to poorer performance. The plots of data of the able-bodied students (upper panels) show a distinct pattern which reflects the degree of difficulty and the actual length of the course. Course 1, the straightaway, was easier (though not physically shorter) than all other courses. Courses 2 and 4 received second-best scores, followed by courses 3 and 5 in that order. The fact that this pattern was repeated across the five driving tasks (WLO and WHI, JP, 2D, and 3D) indicated that the different driving modalities were comparable at least at the level of performance for the courses.

Another reassuring pattern emerged in the plots of the able-bodied students. The mean performance of the students in different age groups was extremely regular and exactly as expected. Again, there was one exception (WLO, Course 3), but the general pattern showed the oldest (8-9 yr.) students to perform best, followed by the 6-to-7 year olds and finally by the youngest students, whose times to complete the courses were the highest.

The pattern of age-related performance differences was expected and confirms both the appropriateness of the task and the qualitative similarity of the tasks.

A closer look at the plots of the able-bodied students also revealed a more subtle age-related difference. Both the Jeep and the 2D task required a higher degree of decentration (i.e. the ability to take a perspective other than one's own, in this case the perspective of the Jeep and the 2D screen cursor) for courses 3, 4, and 5. From the plots of Jeep and 2D data (Figures 8, 9 upper panels) it can be seen that the gap between scores for courses 3, 4, and 5 for the youngest (4-5 yr. old and hence egocentric) group and those for the two older groups is much wider than for the wheelchair or 3D modalities.

Disabled Students

The plots of the mean performance data for the disabled students were not nearly as regular as those of the able-bodied students. Close inspection of the lower panels of Figures 7-11 revealed that the pattern of mean performance per course (1, 2-4, 3, 5) was still present (especially in WLO, WHI, JP, AND 3D) but was violated more often. What was more obvious is the large irregularity in the age-related pattern of performance. Only the data for the 3D driving modality showed the expected pattern of age-related performance. All other driving modalities displayed multiple crossovers in mean performance per course for the three age groups. The relatively small differences attributed to egocentricity in the mean of able-bodied students was completely swamped by other sources of variation in the disabled students' means.

It should be emphasized that although there were differences in the pattern of means for the two groups, the level of performance on the magnitude of the mean scores between disabled and able-bodied was quite similar. Mean performance of disabled students was more variable, but was not entirely out of the range of performance means for the able-bodied students.

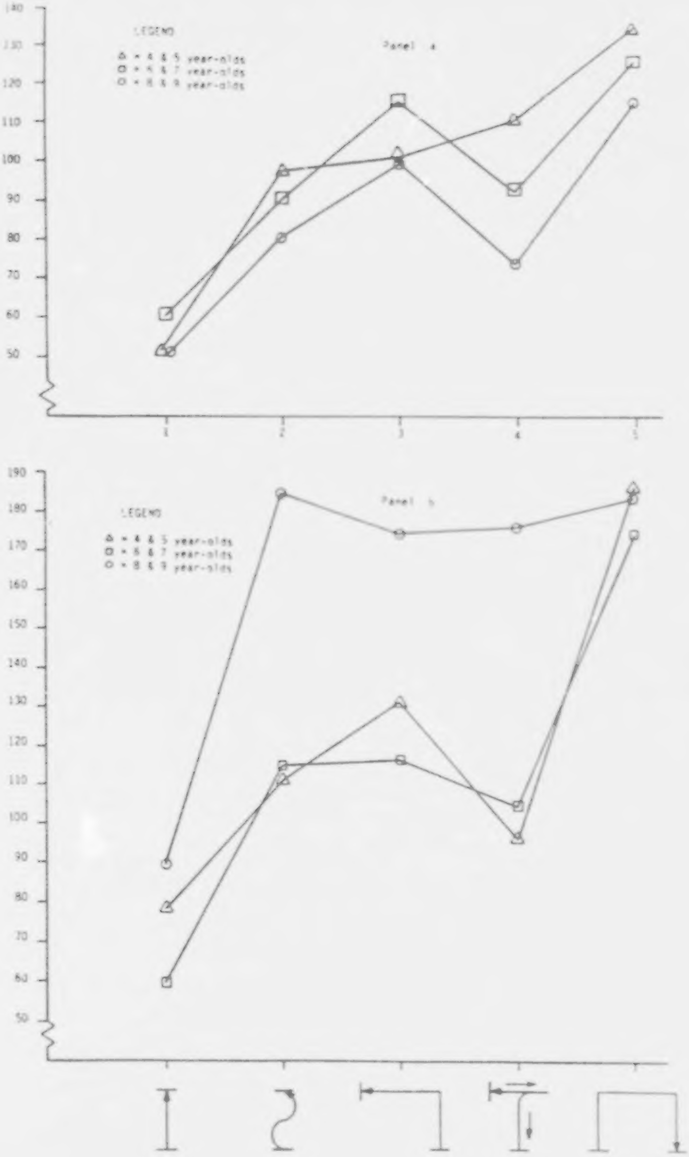

Figure 7: Mean Performance scores for wheelchair at low speed: Paddle reads (time) x courses for three age groups of able-bodied (panel a) and disabled (panel b) students.

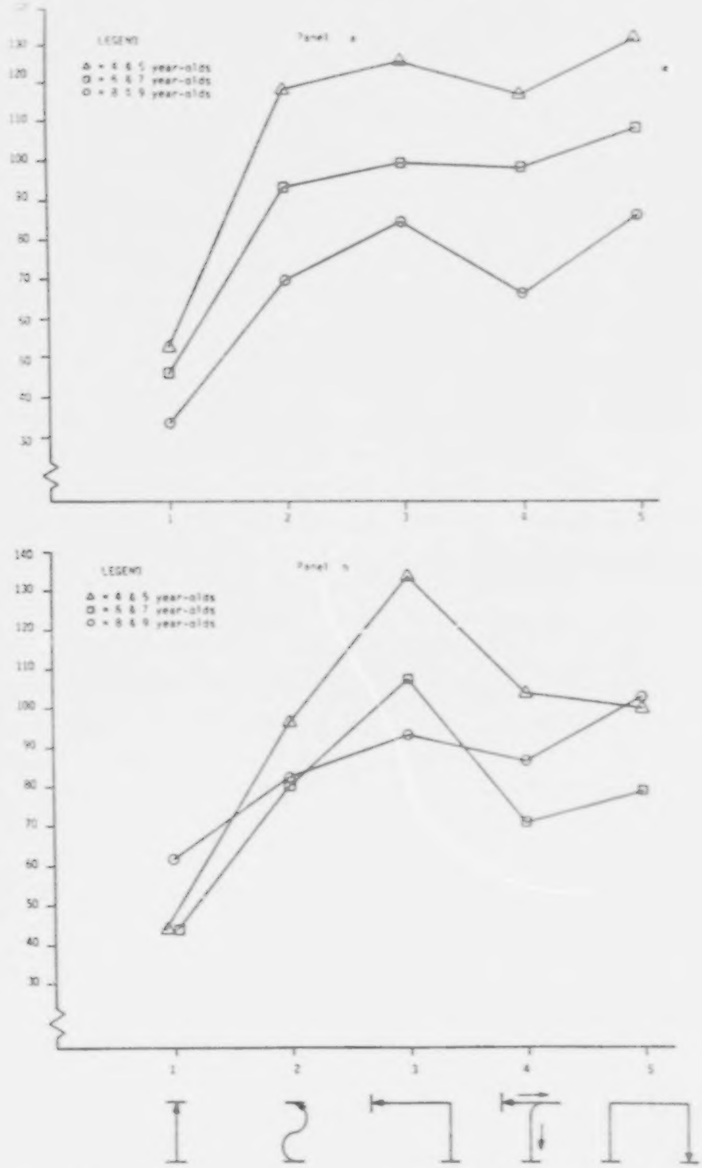

Figure 8: Mean Performance scores for wheelchair at high speed: Paddle reads (time) x courses for three age groups of able-bodied (panel a) and disabled (panel b) students.

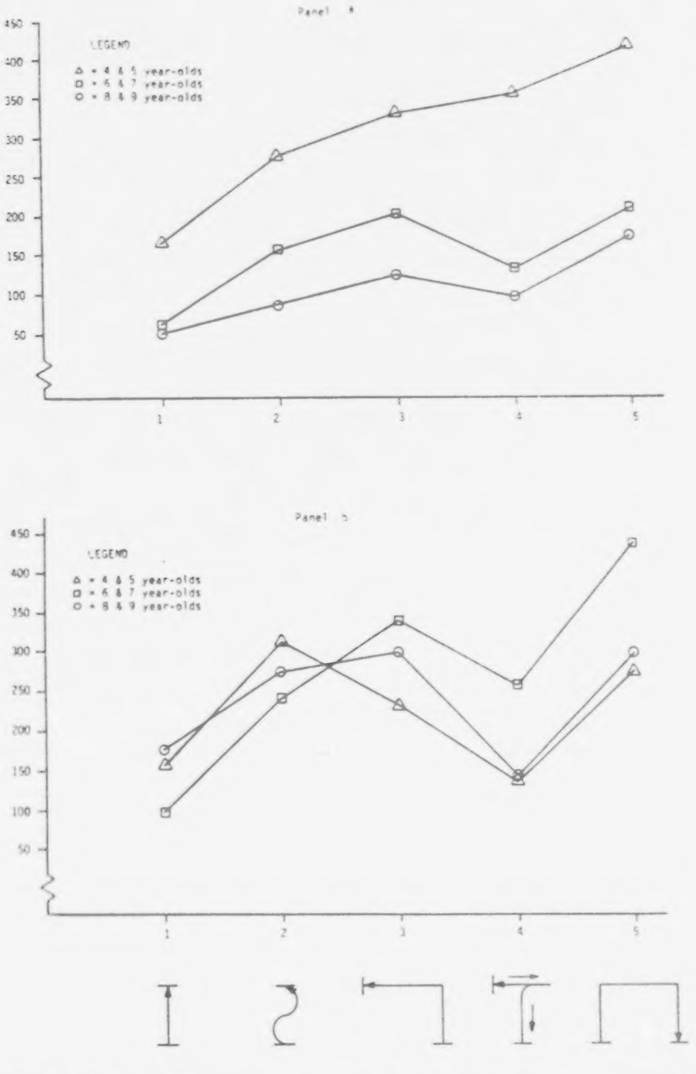

Figure 9: Mean Performance scores for jeep driving: Paddle reads (time) x courses for three age groups of able-bodied (panel a) and disabled (panel b) students.

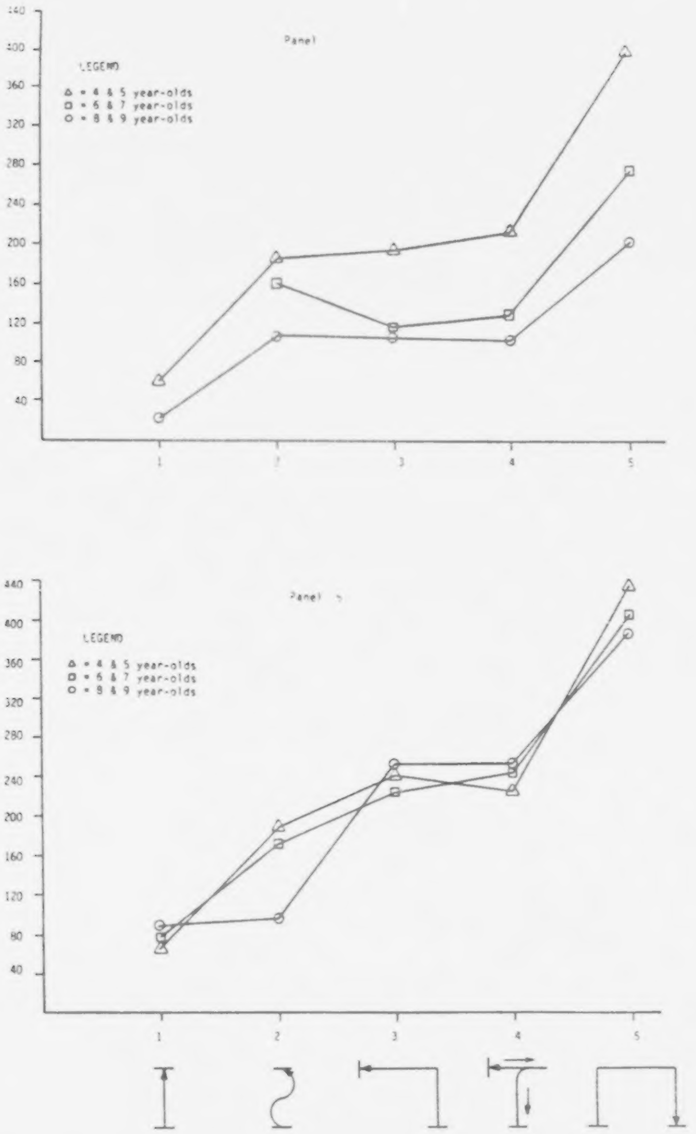

Figure 10: *Mean Performance scores for 2D simulation: Paddle reads (time) x courses for three age groups of able-bodied (panel a) and disabled (panel b) students.*

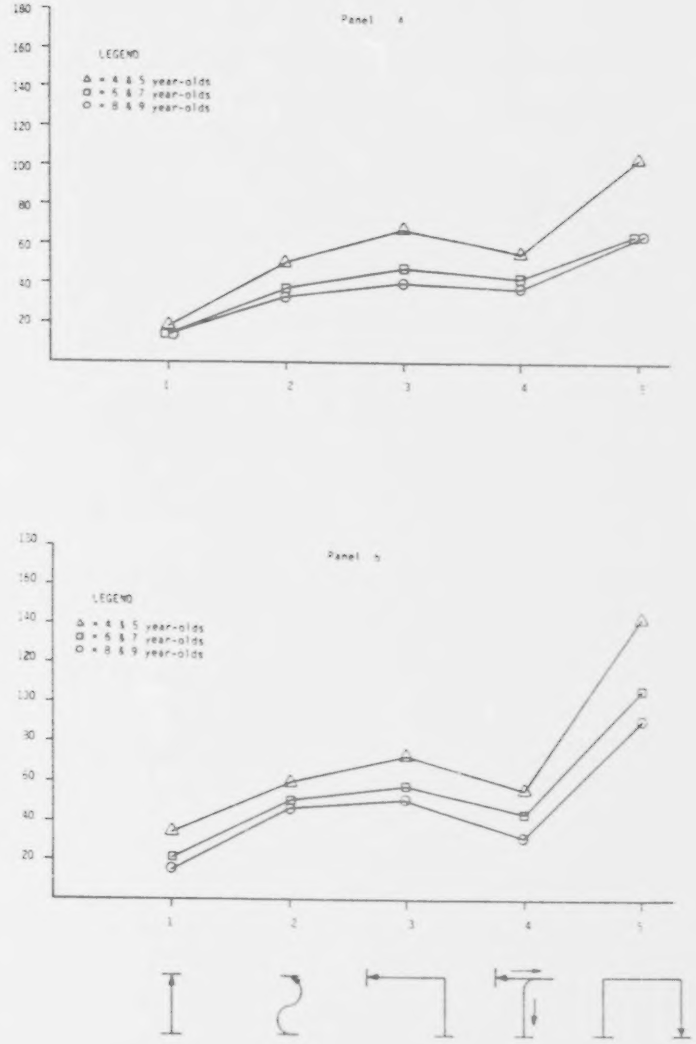

Figure 11: *Mean Performance scores for 3D simulation: Paddle reads (time) x courses for three age groups of able-bodied (panel a) and disabled (panel b) students.*

Perceptual and Cognitive Tests

Mean scores for Peabody Picture Vocabulary Test (PPVT), Picture Completion subtest of the WISC-R, and Motor Free Visual Perception Quotient (MVPQ) results are presented in Figures 12 - 14. Results for the able-bodied students by age group and results for the disabled students (experienced and inexperienced) by age group are presented.

On first impression, these plots are a strong argument for the invalidity of the practice of using tests that are standardized on an able-bodied population as measurement tools for disabled persons. The differences between the two groups are very large and statistically significant ($p < .0001$). Aside from this obvious concern, two other points require attention. First, the verbal (PPVT) and perceptual (MVPQ) scores are very similar for the two disabled student groups. However, the spatial task (Pict. Comp.) shows a much higher mean score for the youngest experienced drivers, while the older experienced student groups have lower mean scores for the picture completion subtest.

The second point of note in the three figures is that while the mean scores for the able-bodied students remain the same or increase slightly from age group to age group, the mean scores for the disabled students generally decrease – in the case of MVPQ, precipitously so – from one to the next higher age group. The most prudent interpretation that can be given for this drop in scores is that it is due to the particular sampling of disabled students in our study. However, the much more worrisome alternative interpretation, that the gap between disabled and able-bodied students' performance (on standardized tests) widens with age, should be seriously considered. If this divergence in performance is not just a sampling error or due to other differences between students in the three age groups, it would indicate that intervention should occur as early as possible; that is, when the gap is narrowest.

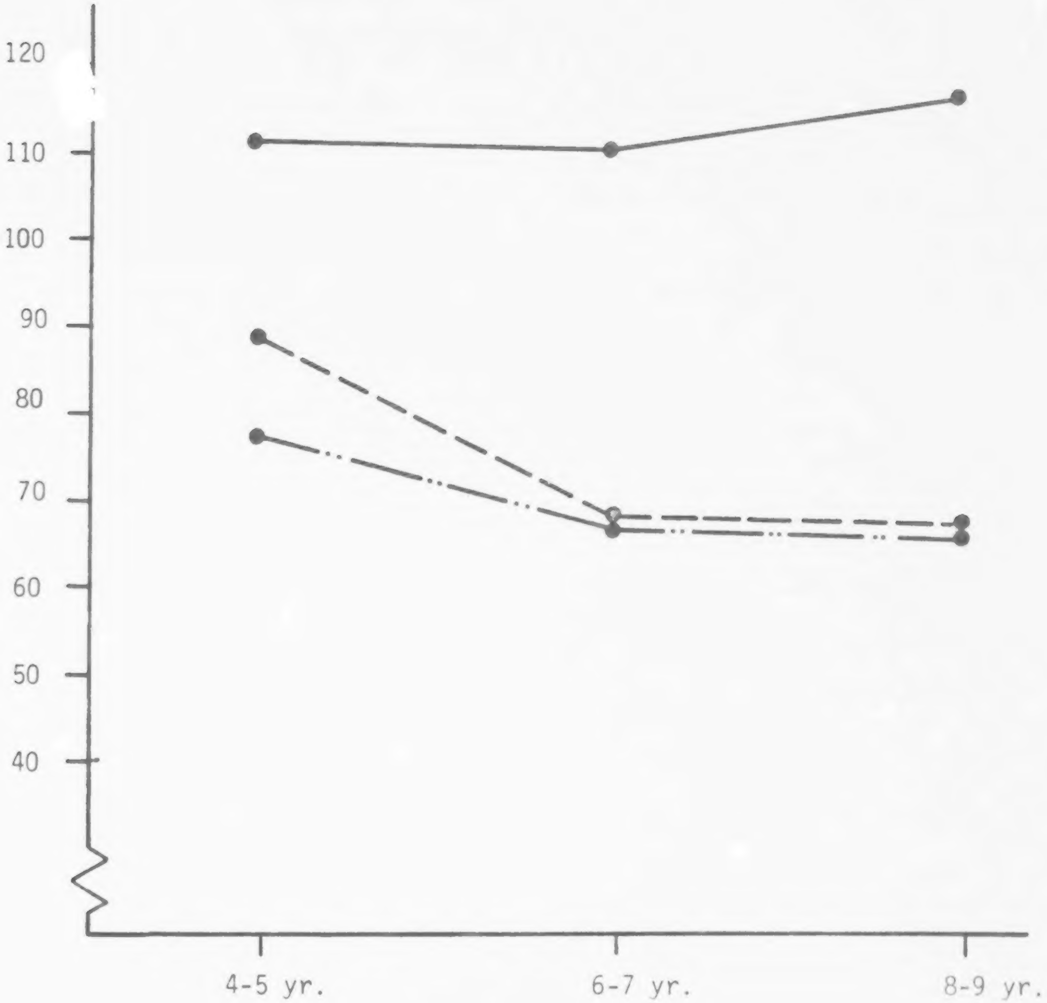

Figure 12: *Mean scores for Peabody Picture Vocabulary Test by age group for able-bodied (solid line), disabled inexperienced (dashes), and disabled experienced (dotted solid) drivers.*

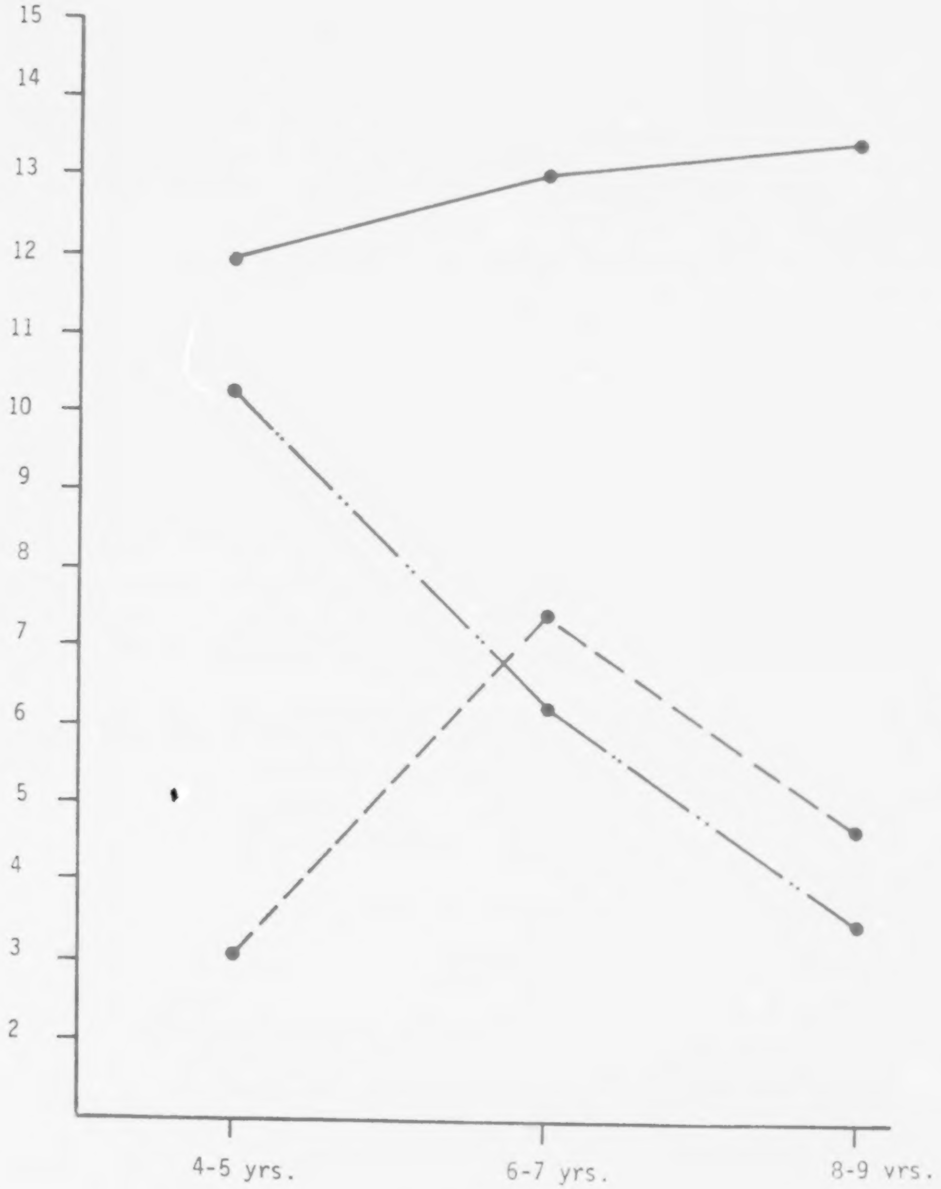

Figure 13: Mean scores for Picture Completion Subtest by age group for able-bodied (solid line), disabled inexperienced (dashes), and disabled experienced (dotted solid) drivers.

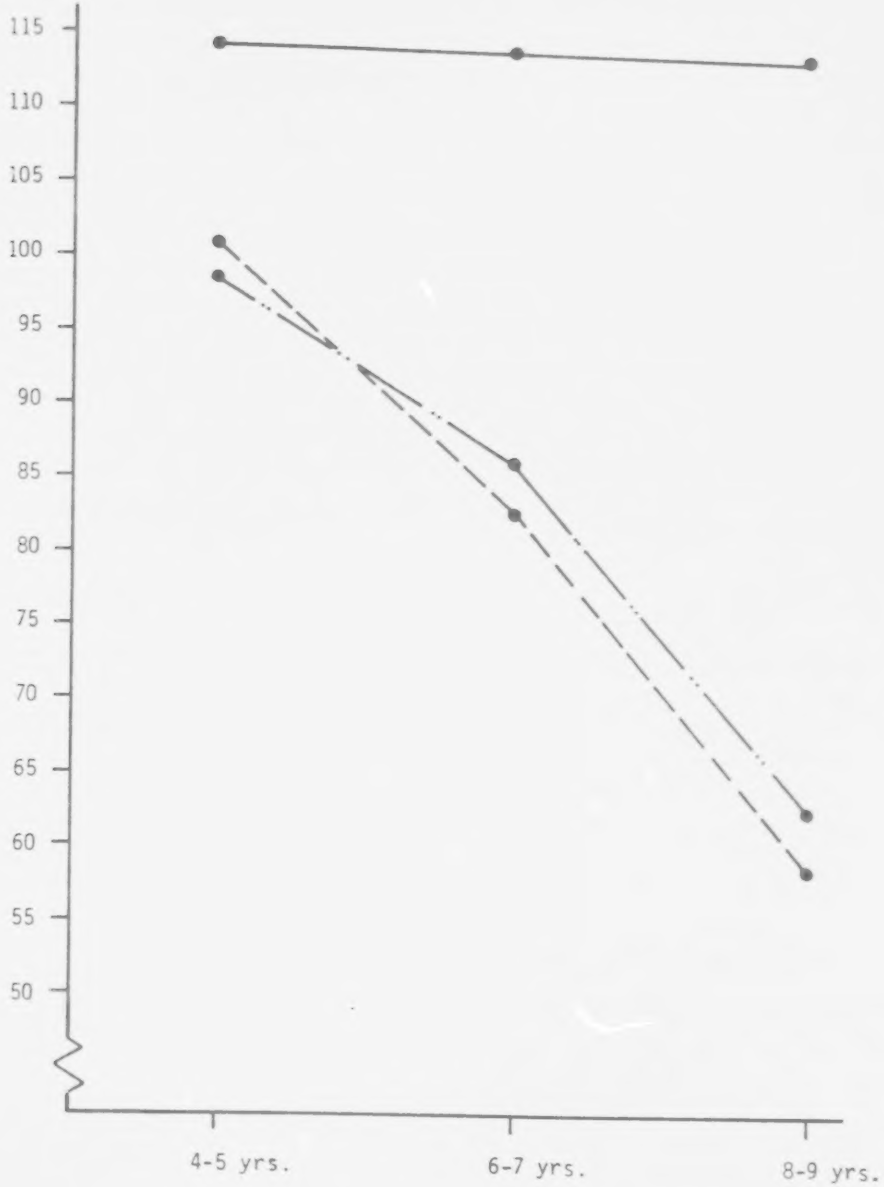

Figure 14: *Mean scores for Motor Free Visual Perception Quotient Test by age group for able-bodied (solid line), disabled inexperienced (dashes), and disabled experienced (dotted solid) drivers.*

Some Statistics

Although the differences in driving test performance between disabled students and able-bodied students are not obvious from the plots of Figures 7 to 11, an ANOVA resulted in significant differences between groups for all modalities except WC driving in high speed. Table 6 presents the p values for the Group (2), Age Group (3), and Course (5) main effects and the Group X Age Group interaction.

Only two other interaction terms were significant, each in one driving modality only. The first two of the non-significant effects (Group in WC high speed, Age group in WC low speed) can be explained from the fact that half of the disabled students were experienced wheelchair drivers. The fact that a group difference does appear in WC low speed driving is most likely due to the fact that the low speed was too low for both experienced drivers and older students. The latter accounts for the absence of a significant age group effect in the WC low condition.

	Group	Age Group	Course	Group x A grp
WC Low Speed	.000	.213	.000	.003
WC High Speed	.746	.001	.000	.050
Jeep	.002	.000	.000	.000
2D	.000	.000	.000	.002
3D	.000	.000	.000	.085

Table 6: P values for ANOVAs (Group (2) X Age group (3) X Course(s) for five driving modalities; Main effects and Groups X Age Group Interaction

Regression Analysis

A preliminary report follows about a regression analysis performed on two small sets of variables. i.e.,

1) Chronological age, PPVT, Picture Completion, and MVPQ, and
2) Performance scores (PRs) for driving modalities.

Since course 1 (the straightaway) was very different from the other courses in terms of task demands, scores for courses 2-5 were combined and analyzed separately from those for course 1.

Regression analyses were performed using chronological age, PPVT standard scores, Picture Completion standard scores and the MVP Quotient as predictors, and scores for course 1 and the mean of scores for courses 2-5 for all modalities as predicted variables. For the able-bodied students, this resulted in two significant predictive relationships. High speed is predicted by chronological age ($p < .001$) and performance on the 2D simulation and on Jeep driving is predicted significantly by Picture Completion subtest scores (p <.001 and p <.005 respectively).

The second set of regression analyses used the performance on other driving modalities as predictors. Performance on courses 2-5 for WC high speed, Jeep and 2D simulation was predicted by Jeep performance (p <.006), 2D performance (p <.014), and by 3D performance (p <.01) respectively. That is, the performance on the Jeep predicts performance in high speed wheelchair driving, performance on the 2D simulation predicts Jeep driving, and performance on the 3D simulation predicts a child's performance on the 2D simulation task. All of these results apply to the able-bodied students only.

The only predictive relationship that emerges for the disabled students is that between the performance on WC high and low speeds, jeep and 3D simulation, all of which predict performance on the 2D simulation. Analysis is continuing to determine more exactly the causes or reasons why performance of the disabled students refutes prediction by the test results analyzed to date.

Discussion

The analyses conducted so far and presented in the preceding sections raise more questions than they answer. The obvious and most frustrating aspect of this preliminary analysis is the high variability in the scores of the disabled students. It is this high variance which reduces the magnitude of the correlations between scores, which in turn results in non-impressive results of the regression analysis for disabled students. A regrouping of students on the basis of physical ability level, current mobility status and diagnosis will be carried out to achieve a more homogeneous grouping of disabled students.

For the able-bodied students, regression analysis results are modest but interesting. Chronological age predicts performance of WC driving at high speed. This is a positive relation; that is, the higher the age the better the performance on high speed WC driving. Picture Completion Test scores predict both Jeep and 2D simulation performance. Thus, a child's ability to identify missing elements in simple drawings, as in the picture completion subtest, is an indication of the child's ability to drive a remote-controlled vehicle or a two-dimensional computer simulated car through a course. The interesting aspect of the regression analysis for able-bodied students is that jeep driving is predicted by a paper-and-pencil test and itself predicts high speed wheelchair driving performance.

When one combines the predictive relationship with the comparability of performance patterns across driving modalities (Figures 7-11), it would appear to be possible to use the alternative driving modalities; if not as predictors, then as potential driving training tools. Results from the regression analysis of data for the disabled students support this interpretation.

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PEDIATRIC POWERED MOBILITY:
SERVICE DELIVERY AND ASSOCIATED RESEARCH

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Introduction

The last decade has seen many changes in powered wheelchairs which reflect changes in the identified needs of disabled populations. Mobility is no longer seen as a luxury for the disabled person, but as an important contributor to lifestyle and self-development. In more recent years the focus of attention has been on disabled children and, in particular, the mobility requirements and possibilities for the very young child. Previous research has shown that very young children are capable of handling powered mobility aids and that their provision positively affects the child and family as well as how the child is perceived in the community (Paulsson & Christoffersen, 1984; Butler, 1984; Verburg et al., 1984). In response to these findings, wheelchair manufacturers are now offering scaled-down versions of powered wheelchairs to be more size-appropriate for the young drivers.

The availability of children's powered mobility aids is only one of the necessary components in providing independent mobility. A number of other factors must be considered in a mobility system, such as the physical limitations of the child and how this might influence the type of wheelchair chosen, the provision of additional postural support, and the type of driving control or interface that may be used. These factors are further compounded when an augmentative communication or environmental control system is added to the mobility system.

The choice of a powered wheelchair is affected by factors such as where the wheelchair will be used (rural, urban or city); how it will be used (indoors at school, indoors at home or outdoors); whether it will require a special seating system; whether the particular wheelchair model lends itself to adaptive controls should the client require special interfacing; how the wheelchair will be transported (school bus, public transportation or family vehicle) and the track record of the local vendor for supporting the particular model of wheelchair (replacement parts, inventory and technical support for servicing).

The Programme

The Interface Programme at the Hugh MacMillan Medical Centre (HMMC) was established in 1977 to prescribe appropriate powered mobility systems for disabled clients and, when necessary, integrate considerations for seating, mobility and communication. The Programme has facilities to develop and provide custom interfaces, on a fee for service basis, when commercial options are not readily available. Where major investigation is required to resolve a particular interfacing problem, external funding is formally sought to support detailed research work. Attempts are made to transfer significant technological developments to the manufacturing sector for commercialization while clinical advancements are shared with the general rehabilitation community. The Programme benefits from having a multi-disciplinary approach to resolving the interfacial needs of clients.

The Team

The decisions made in the prescription of a powered mobility system normally involves team input from medical, therapy and technological disciplines to ensure physiological appropriateness and technological feasibility. From time to time input from other disciplines (social work, psychology and education) may be included as the particular situation dictates.

A medical referral to the Programme is required to address problems concerning the physical status/progression of the client. It is very beneficial at this point to determine if medical goals for the client have been established which may affect the way in which seating and interfacing is approached. The client is then assessed by the team occupational therapist. Once the physical abilities and needs of the client have been documented in conjunction with the client's parents and health care professionals, a meeting is held with the Rehabilitation Engineer to discuss the interfacial needs and to decide on the most appropriate interface. A therapy Remedial Instructor may be required if additional driving training is warranted.

Interaction with other teams within Rehabilitation Engineering is often required where the client has needs for specialized seating or mechanical modifications or attachments to the wheelchair frame. Further consultation may be required with augmentative communication consultants to coordinate the placement of manual communication systems or voice output devices for the non-verbal clients. External collaboration is often sought with the local vendors and with the wheelchair manufacturers as part of the overall team approach to problem solving.

Physical Assessment

The physical assessment looks at the client's voluntary control over their body parts with a view to identifying potential interface sites. Specific factors in the physical assessment look at:

a) Sitting balance

b) Trunk control

c) Head control
  - Can the client see the area immediately in front of the wheelchair?
  - Can the client keep their head in an upright position while the wheelchair is moving?
  - Can head control provide reliable repeatable movements for switch access?

d) Upper extremity control
  - Quality of movement,
  - Movement control grading,
  - Range of movement,

e) Dominance
  - Left/right

f) Type of grasp
  - Palmar
  - Fingertip
  - Active release of grasp

g) Lower extremity control
  - Would knees or feet provide a reliable and repeatable switch site?

h) Reflex movements
  - ATNR
  - STNR, particularly extensor thrust
  - Rooting reflex
  - Associated movements
  - Startle reflex
  - Do these movements interfere with the client's driving ability or switch accessing?

i) Sensory
  - Vision: client may be legally blind but able to see shadows in well lit hallways. This would be acceptable if the client always drives in institutional settings or a protected environment.
  - Restricted field of vision – does client compensate?
  - Hearing is of less concern but is definitely an asset when using interface which provides auditory feedback when activated.

Hearing is important for environmental cuing such as approaching footsteps from behind.

Left-right dominance may be determined by approaching the child from midline and offering a handshake or by presenting a toy. Assessment of independent trunk control will identify if special seating will be required to promote stability and improve physical/functional output for interface access. Independent trunk control will also determine to some degree the type of wheelchair which may be prescribed. A three wheel scooter type powered mobility aid generally requires good head and trunk control, good sitting balance, moderately good upper extremity control and voluntary grasp/release.

Pre-Driving Skills

The use of computer aided assessment techniques for determining the appropriate interface type and placement for powered mobility has been investigated, but currently with limited clinical applications (Basacchi et al., 1981). Another research project investigating the predictors of powered mobility was recently carried out at HMMC. Some of the results of this project are described elsewhere in these proceedings (Verburg et al., 1984).

Functional assessments for driving powered wheelchairs are currently performed clinically, at HMMC, through assessment wheelchairs. These powered wheelchairs include Everest & Jennings Models 3W, 34 and Scout MPV, Fortress Scientific Models 1000, 2000 and 655 and a custom miniature powered vehicle developed as part of a pediatric mobility research project at HMMC. Occasionally arrangements are made with a local vendor to loan a mobility aid or interface to assess the unusual client. The wheelchairs have a variety of commercial interfacing options as well as a number of custom interfaces used regularly by the Programme. The subjective selection of an interfaced mobility system resulting from the client's physical/functional assessment can immediately be tried under dynamic conditions to determine appropriateness. If the first selection does not seem quite right, another interface configuration can be set up immediately.

Clinically, certain basic skills appear necessary for effective wheelchair driving. An understanding of cause and effect is required, otherwise the client may not recognize that he is causing and is responsible for the movement of the wheelchair. This has repercussions in the understanding of how to stop the wheelchair, which is an important safety factor to the driver and those in the proximity of the wheelchair. If the client does not learn to stop the wheelchair before hitting people or objects, without continuous reminders, an electric wheelchair is not prescribed.

If these skills are not apparent during our functional assessment, methods of developing them are suggested to the parents and caregivers. The provision of single switch toys that provide good visual response, when the interface is activated, is an initial step. The action of the toy may progressively become more remote or abstract such as radio-controlled toys or a tape recorder where visual stimulus is not present. Additional switches and toys may be provided to allow independent choice as to which toy is activated. The use of cause and effect computer programs controlled by a single switch, such as scanning routines and drawing programs like Logo, may train switch use and develop a sense of directionality.

We have noted an obvious difference between clients who have had some self-propelled mobility and those who have not had that opportunity. Those clients without some prior control of mobility (crawling or rolling) have difficulty with directionality. The concepts of turning the wheelchair appropriately and moving towards or away from an object such as a wall are difficult for them. Their prior passivity can be likened to an automobile passenger who pays no attention to where the car is going. That passenger may be unable in the future to find the same destination; the passenger was unaware of and not responsible for directing the movements of the car.

For the severely disabled non-mobile client even the language of motion may not be familiar. Using the terms STOP/GO, FORWARD/BACKUP, LEFT/RIGHT and TOWARDS/AWAY FROM may be the first steps towards teaching directionality. Having the client seated in a manual wheelchair and directing the person pushing the wheelchair when and where to stop/turn may be the first steps in decision making. These decisions may be indicated by eye or a wide variety of body movements. The destination may initially be the next room and expand to a familiar location in the neighbourhood. The client must also be familiarized with "the rules of the road" such as when to stop for pedestrians and motor vehicles. Children's games like "May I?" and "Red Light, Green Light" may reinforce these lessons.

Training

After the client has the basic understanding of stopping and directionality and the physical assessment has determined the most probable method of wheelchair control, training is required to teach this method of control. Occasionally two control methods are taught simultaneously and after sufficient training the more efficient control method is chosen. The training sessions are really practice sessions and the amount of training time required is dependent on the particular child and the complexity of the interface being used. The most difficult interface on which to train clients is the scanning interface, probably because there is very little correspondence between the body movements made to control the interface and the actual movements that the wheelchair makes as a result. Training a client to use switches for controlling computer programs normally only trains the client to momentarily respond at appropriate times to obtain a certain action from the computer. In wheelchair driving, the client must be trained to maintain contact with the switch in order to maintain the motion of the wheelchair. While it is possible to have wheelchair controls which will maintain motion of the wheelchair with only a momentary contact with the interface switch (latching switch), this would create a very unsafe driving condition for the unskilled driver and those drivers with motoric impairment. A latching switch would better apply, in a limited manner, to clients who have limited strength and endurance but still have good dexterity.

Wheelchair Selection

Many trade-offs, in areas such as image, function and adaptability, must be made in the selection of a powered wheelchair. The image of the wheelchair becomes part of the client's personal appearance. The importance of this image becomes more significant towards adolescence and beyond. Clients who have a deteriorating physical condition may not want to use an electric wheelchair initially since it portrays them as handicapped. The powered scooter is usually more acceptable in this situation. Scooters have the positive aspect of being cheaper than electric wheelchairs and are easier to transport in the family car as opposed to a van. Good sitting balance and upper extremity function usually are required for this type mobility aid. On the negative side, the concern that scooters cannot be properly secured in buses has been voiced by public transportation groups for the disabled. The disabled person must be capable of independent transfer to a regular vehicle passenger seat and use conventional seatbelts while the scooter is separately secured to the frame of the bus.

This point of public transportation raises another issue with some school bus lines. If the client expects to be transported to and from school in a powered wheelchair, it would be wise to check with the transportation company regarding their policy on storage batteries. Some transportation companies will not allow conventional wet acid batteries to be transported, but require that the wheelchair be used with gelled electrolyte batteries.

The function of the wheelchair is mainly limited to where the wheelchair is to be used the majority of the time. If the wheelchair is to be transported in the family car it may be desirable to have either a lightweight powered wheelchair such as an ABEC, a manual wheelchair with an add-on power pack such as the Fortress Model 1000 or a powered base (Walder, S., 1980) type of wheelchair which can be dismantled like the Everest & Jennings Explorer. The latter powered base type of chair does disassemble into component parts (each of which weighs no more than 40 pounds) but would normally only be disassembled for the exception rather than the rule. Light-weight powered wheelchairs tend to also be light duty wheelchairs. These might be expected to be used primarily indoors and for limited outdoor use, such as on sidewalks and well groomed lawns, and with a moderate driving range per battery charge. The more conventional style of wheelchair would extend the driving range of the wheelchair and the outdoor use. The powered base wheelchair, with its lower centre of gravity and wide pneumatic tires, is probably the best for outdoor activity. It has the same driving range as conventional powered wheelchairs. The wide pneumatic tires that are an asset on sand and gravel outdoors make the wheelchair difficult to turn on pile carpeted floors.

The adaptability of the wheelchair determines what types of seating can be used in the wheelchair and how easy it is to provide alternate driving controls if the client is unable to use the standard proportional joystick. In the last few years the major wheelchair manufacturers (Everest & Jennings, Fortress and Invacare) have introduced add-on boxes for their powered wheelchairs which allow the vendor or clinician to plug in their own interface switch arrangement in place of the proportional joystick. These adaptive units are:

Everest & Jennings: Pilot 3000 for Mod. 3P and 3W
Everest & Jennings: Pilot 5000 for Explorer
Fortress Scientific: Commander for Mod 650, 655, 755
Invacare Corporation: Arrow Switch Control Option

These adaptive units are usually a little cheaper if they are ordered with the wheelchair in place of the joystick. They can be added to the wheelchair at any time to meet the needs of a client with a changing medical condition. Switch input options are available from the wheelchair manufacturers and from rehabilitation aid companies like TASH (Technical Aids and Systems for the Handicapped).

Interfaces

Proportional Joysticks: The proportional joystick is the standard type of control provided with commercial powered wheelchairs and provides the user with infinite control over the speed and direction of the wheelchair. This control is usually associated with clients who have good manual dexterity. There are some exceptions to this in the cerebral palsied population. The client may have the ability to control the proportional joystick once the proper grasp has been established. The ability to grasp the joystick may require the addition of a joystick extension. Commercial joysticks usually have mechanical problems trying to deal with the extreme forces that this type of client can exert. This problem is further compounded if an extension handle has been added. Previously this type of client would have had to settle for an interface which would not allow the same quality of direct control that the proportional joystick could provide. The Interface Programme developed a solution to this, called a Heavy Duty Joystick, through the use of a military style proportional joystick and adapting this joystick electronically to be used with a number of commercial wheelchair controllers. This joystick is currently available for Everest & Jennings 3P and 3W, Invacare Arrow and Fortress 650, 655, and 755.

Another proportional type of joystick that is commercially available is called the RIM (Rehabilitation Institute of Montreal) control. This interface is mainly used by the spinal cord injured population and is controlled by placing the head in a "Y" shaped yolk mounted behind the head. Pushing the head backwards causes the wheelchair to drive forward at a speed proportional to how far the heads has been pushed back. Rotating the head left and right cause turns proportional to the degree of head rotation. Two other momentary switches must be used with the system. One switch alternates the wheelchair control ON/OFF and the other switch alternates the head control between FORWARD and REVERSE driving. This type of control is available from Everest & Jennings and Fortress Scientific.

Non-Proportional Joysticks: The non-proportional joystick interface must dissociate the speed control function from the joystick and provide only directional control. Usually coupled with this type of ON/OFF or digital interface is a wheelchair controller capable of independently controlling acceleration and deceleration and a means for presetting the maximum speed of the wheelchair. There are interfaces which actually physically look like joysticks and there are others which only respond like joysticks. Examples of non-proportional joystick type interfaces are:

Burgess Switch Co: Joystick controller
  (HMMC, Du-it and Invacare)
TASH: Short throw joystick
Du-it Controls: Touch Disc
HMMC: Miniature Touch Plate

Independent Multiple Switch Control: The control of a wheelchair can be directly accomplished by five separate switches either used discreetly or in combinations for additional functions. Typically, there would be a separate switch for FORWARD, REVERSE, LEFT, RIGHT and the fifth switch is used for an ON/OFF or mode control. The mode control could accomplish other tasks such as selecting the maximum speed of the wheelchair or allow the directional switches to perform another function when the wheelchair was not being driven such as environmental control or operate a reclining mechanism. A number of types of switches are available and include microswitches, membrane switches, pneumatic pillow switches and capacitive touch switches (Snell, 1981). Separate directional control switches may initially be used to teach a new driver directionality and cause and effect even though sufficient physical function may be present to operate a joystick control. When these concepts have been learned, the joystick method of control will then be taught.

Microswitches require a reasonably light force to activate, have short button travel and come in a number of shapes and styles. This switch is usually sensitive to overstressing and must be protected from mechanical abuse.

Membrane switches are available singularly and in switch arrays such as those available from TASH. The advantages of this switch are the bright colours available for the switch button area, light force required to activate the switch even when wearing gloves and is fairly resistant to mechanical overstressing. The surface of the switch is resistant to abrasion and cutting but can be damaged with sharp instruments like a pencil. The major problems with the membrane switches is the environmental seal between the elements of the membrane and also where the cable connection is made. Some very sensitive switches have a small air hole to allow the air between the membranes to be expelled when the switch is depressed. This air hole also allows liquids and dust to enter between the membranes and causes the switch to short circuit or open circuit respectively. This problem is particularly evident with single membrane switches from TASH.

Pneumatic pillow switches are not very frequently encountered but are activated by pressing on an air pillow and the change of internal air pressure causes the switch to activate. This may not be a good wheelchair control because exposing these switches to the warm summer sunlight or any other extreme changes in temperature also causes a change in the internal pillow air pressure and the switch to activate.

Capacitive touch switches have the advantage of taking almost no force to activate the switch, are equally sensitive over the entire button area and are immune to mechanical overstressing. The button area is a piece of stainless steel sheeting (thus, it is relatively food proof) and can be cut to whatever size and shape the client requires. The capacitive switch requires actual skin contact so can not be activated through gloves. The operation of this switch is further affected by very dry skin in the winter and very humid conditions in the summer. Dry skin acts as an electrical insulator and prevents the body part from contacting the switch, while the humidity is a conductor and tends to short circuit adjacent switches. The dry skin condition can be overcome by applying a small amount of hand cream to the body part activating the capacitive touch switch. This interface is available from HMMC in the form of an assessment system, miniature control and as a custom lap tray.

Scanning Interfaces

The scanning interface is probably the slowest interface to use for driving a wheelchair, but it requires the least motoric input to operate. Scanners come in different forms and can be activated with one, two, three or four switch inputs depending on the physical capabilities of the client. All scanners have a display panel with a listing of the available function that can be chosen. In the minimal form these functions would be FORWARD, LEFT, RIGHT, REVERSE and ON/OFF with a small lamp that indicates when each function is chosen.

Single-Switch Scanner: A single-switch scanner usually has one of the functions designated as a "home" position. This is the function that will be lit when the scanner is in a dormant state (probably the ON/OFF function). The scanner is activated by momentarily touching the interface switch, which causes the scanner to sequence through the functions at a rate which is preset for each client dependent on his reaction and release capabilities. The scanning rates will normally be in the range of 0.5 seconds to 3.0 seconds between function steps. The interface switch must again be closed and held closed when the desired function is lit. The wheelchair will then move in the selected direction as long as the switch is held closed. Once the switch is released, the scanner continues to sequence through the functions until the switch is again closed. This could be somewhat frustrating for an individual who has trouble maintaining continuous contact with the switch either due to motoric control or the dynamic movements of the wheelchair. Time delays can be built into the interface switch response that will cause the scanner to ignore a momentary release of the switch, but this time delay will also cause the wheelchair to run on when the switch is intentionally released to stop. Scanners are usually set up to return "home" and the dormant state if the interface switch has not been activated after all functions have been scanned a few times.

Two-Switch, Step Scanner: A two-switch scanner uses one interface switch (SCAN) to control the scanning of the functions, while the other switch (SELECT) causes the desired function to be selected. The wheelchair will continue to move as long as the SELECT interface switch is held closed. A step scanner will step one function each time the SCAN switch is closed. This type of scanner is cognitively easier to use than the other scanners and may be used a training tool to allow the client to progress to a more advanced type of scanner.

Two-Switch Auto Scanner: The auto scanner operates similarly to the step scanner except that closing the SCAN switch causes the scanner to automatically sequence through the functions. The next time the SCAN switch is closed, the scanner continues to scan from the last selected function. Like the single switch scanner, the rate at which the functions are scanned is preset for each client.

Two-Switch Auto Scanner with Auto Reset: This scanner operates similar to the auto scanner except that instead of continuing to scan from the last selected function, the scanner automatically resets to a particular function such as FORWARD. This has the benefit of reducing the overall scanning time, since FORWARD is the most frequently selected directional function.

Three-Switch Scanner: The three-switch scanner operates similar to the single switch scanner except the additional two switches allows the wheelchair to be veered to the left and to the right for course corrections while either the FORWARD or REVERSE function has been selected. This method of scanning is not frequently used but, if the client can access the additional two switches, will reduce scanning time.

Four-Switch Scanner: The four switch scanner operates like any one of the two switch scanners except the two additional switches allows the wheelchair to be veered to the left and right for course corrections while either the FORWARD or REVERSE function has been selected.

The Interface Programme had previously developed a scanning interface and now a microprocessor based scanning interface that will perform the various scanning techniques previously described (Antczak & Snell, 1983; Shire, 1987).

If a scanning interface is used in conjunction with one of the commercial wheelchair controller switch adapters, consideration will have to be given to the cognitive abilities of the particular client. The client will have to understand how to scan his adaptive controller to the desired wheelchair function (wheelchair speed or environmental control) and then understand how to operate his scanning interface to drive the wheelchair in a particular direction. In this case, the client must comprehend two different scanning techniques and that their interface switch(es) performs different functions depending on the task being performed. This becomes even more complicated if the same interface switch(es) must also operate a scanning type of communication aid or computer program.

Conclusion

Powered mobility has come a long from just the basics of moving from one place to another. The electronics controlling the drive of the wheelchair has enhanced the performance of the wheelchair by adding in cruise control features and the ability to control static parking brakes. Some wheelchair manufacturers are allowing for the control of other electronic aids through the wheelchair's controller. New interfacing techniques and procedures now allow children independent mobility who would otherwise have been passively mobilized quite dependently. Mobility enhances the quality of these lives, but the question remains: where do we go from here?

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POWERED MOBILITY FOR SEVERELY PHYSICALLY DISABLED CHILDREN: EVALUATION AND PROVISION PRACTICES

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Abstract

The trend of considering powered mobility devices for young, severely physically disabled children is growing. It is through movement that children learn, not only about their environment, but also the true essence of the feeling of independent mobility.

Today more than ever before, there are sophisticated evaluation tools and technical solutions to the seating and mobility needs of the severely disabled young child. Several major obstacles to providing appropriate technical solutions, including professional/parent attitudes and funding, still remain. Research findings and clinical experience indicate the advantages of independent movement for very young disabled children.

Introduction

Powered mobility for children with physical disabilities is very slowly becoming a reality. However, despite documentation of the need for independent mobility and its benefits, the increased availability of technical options and more published reports, only a small percentage of the children who could benefit from powered mobility are being given the option. The example of the Shrine School (a public school for children with physical disabilities) in Memphis, Tennessee, illustrates this situation. In the 1972-73 school year, there were nine children of a total enrollment of 172 who used powered wheelchairs. Of the nine, eight had a diagnosis of Duchenne muscular dystrophy and used powered wheelchairs owned by the school. The ninth child was a quadramembral amputee who had his own powered wheelchair. All users were boys over ten years of age. Today the picture at Shrine School is quite different. There were 121 students enrolled in early 1987, of whom 22 are ambulatory and another 21 are ambulatory with assistance. Of the remaining 78, 47 are using manual wheelchairs, 27 are using powered wheelchairs and three are using other forms of powered mobility. Only four of the powered devices belong to the school – and they are four of the original eight which were purchased in 1972. The remainder of the powered devices are owned by the children and were purchased by families, community groups, or Medicare/Medicaid. It is interesting to note that of the ambulators, six have manual wheelchairs available for periodic use. Of those children using manual wheelchairs, the occupational therapist felt that four needed to be referred for consideration for a powered device.

The increased numbers of independently mobile young disabled children, including some who are very severely motor-impaired with little or no use of their hands, represents a growing trend. Of the total number of children at the school, 24.7% have powered mobility devices. By far the largest diagnostic category of children in powered devices is cerebral palsy. The other notable trend is for children to be given powered devices much earlier. The Shrine School accepts children who are between the ages of 5 and 21 years. In the mobility survey, there are 7 out of 121 children between the ages of 5 and 10 years who have powered devices, while in 1972 there were none. Those of us who feel strongly that all physically impaired children have the right to have powered mobility carefully considered find the traditional philosophies of some of our colleagues and children's parents to be limiting.

Traditionally, powered mobility was made available as a last resort and only to the adult population. Professionals felt that powered devices were too expensive and that children were not sufficiently mature to duly respect such a high-cost technical aid. It was felt that the walls of homes and schools would be in jeopardy as children would have difficulty learning to control battery powered devices. Families were told that transportation of powered wheelchairs was difficult and purchase should only be considered if the family owned a van. Therapists were adamant that children should never be given a powered wheelchair if they had any potential to propel a manual wheelchair, feeling that the child should be using his own motor abilities in order to remain functional. The common exception was young adults with advanced muscular dystrophy. Finally, it was felt that any child with mental retardation would never be capable of learning to operate and care for an expensive and complex technical aid.

Studies of normal child development, however, reveal the critical importance of independent movement. Piaget and Inhelder (1956) stated that infants' early sensory-motor experiences are the basis for learning. Held and Hein (1963) noted that cats who were passively manipulated through a maze did not learn the route, whereas those who moved by their own volition did. In similar research projects, it was found that humans who propelled their own wheelchairs learned a maze while those whose chairs were pushed did not. Wedell (1963) found that children who could not move independently through space were deficient in depth perception. Dennis (1973) studied children in orphanages who were deprived of normal opportunities to move and to receive sensory input and found a generally low level of intelligence. Zubek and colleagues (1963) also observed deficits in cognition and behavior when mobility was restricted along with other sensory deprivations. Tatlow (1980) documented passive attitudes and vague body images in children who could not move independently.

In the past ten years, a number of research projects monitoring the use of powered mobility systems by children have shown impressive results. Physically disabled children as young as 24 months, an age at which normal children have developed independent mobility skills, were found to be able to safely operate powered mobility devices (Butler et al., 1983).

Another study found that disabled children who used such devices became less dependent on controlling their environment through verbal commands, more interested in all mobility skills including ambulation, and much more interactive with peers (Paulsson & Christoffersen, 1984). In addition, self-image improved considerably and attitudes toward approaching new tasks became much more positive (Trelfer & Taylor, 1984).

Such research results and clinical observations have come at a time when many of the traditional technical obstacles are being overcome in the commercial sector. Cost, transportation and accessibility are still problems; however, folding models of powered wheelchairs as well as add-on units are becoming available from a number of commercial sources. Carts, buggies, three-wheel vehicles, and other mobility systems with optional power are being designed especially for children.

Evaluation for Powered Mobility

In considering a young severely physically disabled child for a powered mobility system, the child's seated posture becomes critical. In order to enable the child to perform the motor skills necessary to operate a joystick or push a switch, their posture in sitting must be very stable. This is especially true for children with severe athetosis or very hypotonic trunks. Principles for seating the physically disabled child are already available in several clinical publications (Bergen & Colangelo, 1985; Trefler, 1984).

However, many children are evaluated for powered mobility at the same time as they are evaluated for their seating needs. At the time of the mobility evaluation, most children do not yet have their customized seating system.

Prior to 1985, mobility evaluations for children often had them placed in ill-fitting powered wheelchairs to see if they had sufficient motor skills to operate the device. Either they sat on the therapist's lap, with the therapist offering some stability, or a series of belts, foam pads, and cushions were used to provide limited support and stability. As more severely physically involved children were referred for evaluation, the makeshift evaluation system became totally ineffective. A system of providing temporary customized positioning in a powered wheelchair was required. As no such device was available commercially, nor to the knowledge of the UTREP staff was a design for such a device available in any of the many clinical programs in which our fellow professionals were working, we designed what we believe to be a much needed evaluation tool.

At the UTREP, we have combined a method to provide temporary custom seating (Bead Seat System, Hobson, 1987; Pin Dot Products) in a powered base (Fortress Scientific) with multi-adjustable control location (Magic Arm Camera Mount; Beneficial Designs) (Taylor, 1986).

Since July, 1985, 20 individuals ranging in age from three-and-a-half to 21 years have been evaluated in the mobility evaluation system. Eighteen the children were diagnosed as having cerebral palsy, and two children had cervical spinal cord injuries, one from birth and one from a gunshot wound. All but two of the children had been positioned in specialized seating for at least a year. Seven of the children were initially considered very marginal candidates for powered mobility. All were able to successfully maneuver the chair in an open space within an hour.

The Evaluation Process

The evaluation process consists of three basic steps:

1. creating a customized seating system,
2. introduction to the powered wheelchair,
3. experimentation with movement of the powered chair with the input method that has been matched to each child's functional abilities.

Two case studies are presented to illustrate the evaluation process for powered mobility technology for the severely physically disabled child.

Case #1

Andrew is a six year old boy with a brain stem injury secondary to a gunshot wound at age three. He was referred to UTREP primarily for seating. Upon interview, the parents revealed that they were very interested in obtaining powered mobility, but were unsure if their son had the motor ability to operate a wheelchair control. Andrew's physical/functional data were as follows:

(1) Neuromuscular summary: Moderate spasticity was present in all four extremities. He tended to posture in an asymmetrical tonic neck reflex (ATNR) pattern combined with total body extension to the left. Midline posture was only possible when his head was manually brought to midline. No voluntary motion was present below the chin.

(2) Orthopedic summary: He had bilateral plantar flexion contractures. No other deformities were present.

(3) Functional skills summary: He had good use of all facial musculature once his head was positioned in the midline.

(4) ADL summary: He was totally dependent in all activities of daily living, but his parents tried to provide him with choices about daily activities to encourage decision making/problem-solving skills. Andrew took some food by mouth, but received most nourishment through a gastrostomy tube. He presently has around-the-clock nursing care.

(5) Communication: He spoke during the exhalation cycle of his respirator.

(6) Sensation: There was no sensation below the C_{1-2} dermatome.

(7) Education: Andrew was functioning at the first grade (age-appropriate) level. He received private tutoring through the local school district. He did all of his work verbally, although his parents were asking about the feasibility of him operating a computer for schoolwork. He was already playing games with an Atari joystick held under his chin.

(8) Psychosocial Considerations: Parents were unsure of Andrew's abilities in relation to what technology could provide. Andrew was very eager to be mobile. The home was wheelchair accessible. The family owned a van with a lift.

The neighborhood was in a suburban area with paved roads and sidewalks. The parents intended to bring Andrew to school for two hours per day as soon as he was comfortably positioned. Andrew was the youngest of four boys.

Results

Andrew was positioned in the mobility evaluation system. Special care was taken to obtain a midline neutral head position to reduce the A.T.N.R. and resultant asymmetrical hypertonicity. The joystick was positioned diagonally in relation to his chin. Because of the short leads from his respirator, he was only able to move in a small restricted area, but he immediately demonstrated knowledge of how to use the directional positions on the joystick. He was evaluated over a period of about 30 minutes.

Recommendations

(A) Seating: The Shapeable Matrix seating system (Pin Dot Products) was chosen because of its ability to provide total body contact, aggressive midline positioning, and growth. Because it was an open matrix, there was ventilation to prevent overheating. With this system, his head could be well positioned in midline to allow the relaxation necessary to provide him with the control to operate the joystick.

(B) Wheelchair Base: The Fortress Scientific 655 FS with the TASH micro-joystick (with push feature), joystick mounting hardware and Commander System, and a wheelchair frame seat, was chosen. This particular wheelchair was chosen for several reasons: (1) it was a durable, heavy duty wheelchair that could accommodate the seating as well as Andrew's respirator and suction equipment; (2) the micro-joystick required little force/excursion to operate and (3) it allowed for the use of three speeds, environmental control, and a tape recorder through the commander system, accessed by the joystick. Channel changing between functions was achieved by pressing directly down on the joystick until a "beep" was heard, and the appropriate light emitting diode on the control panel was lighted.

Andrew was seen three months after the evaluation for the actual provision of equipment. Once the seating and other wheelchair modifications were completed, the joystick was positioned utilizing the standard chin control mounting hardware. Andrew immediately drove the chair indoors with no problems at low and medium speeds.

Three weeks after provision of the mobility system, a letter was received from the family indicating that Andrew's attitude toward approaching individuals and tasks had changed. He had become more enthusiastic and cooperative, and was even playing guard with the neighborhood children in driveway basketball games. His brothers had begun to see him not as their dependent little brother, but as more of an equal in the family. Andrew has now had the system for one and a half years. He is in the process of learning Morse Code so he can access an Apple computer with the Adaptive Firmware Card using his wheelchair joystick.

Case #2

Walker is a five year old boy with a diagnosis of spastic quadriplegic cerebral palsy. He had been seen by the UTREP for approximately three years for adaptive seating in a manual wheelchair base. Since he had no ability to functionally propel a manual base, powered mobility was recommended to the family. Because Walker's functional skills were fairly limited, a powered mobility evaluation was done to determine the type of wheelchair and control that would be appropriate for him. The evaluation summary follows:

(1) Neuromuscular summary: Walker had moderate spasticity in all four extremities, with hypotonicity predominant in the trunk. He demonstrated an asymmetrical tonic neck reflex, greater to the left, a symmetrical tonic neck reflex, and an extensor thrust that

predominated in sitting. He sat with a mildly posteriorly rotated pelvis and mild kyphotic posture.

(2) Orthopedic summary: Walker had no relevant orthopedic problems or fixed deformities.

(3) Functional Skills summary: Walker's upper extremity and fine motor skills were quite limited. He could point on command to objects within a small area on his wheelchair tray. He was able to reach, aim, and grasp, but could not maintain grasp on an object. He was left-hand dominant. Unsupported, he could roll both ways, and could sit briefly if placed in a sitting position.

(4) ADL summary: Walker was dependent in most activities of daily living. He could accomplish some finger feeding, and was toilet trained. He was dependent for transfers, dressing, feeding with utensils, and hygiene.

(5) Communication: Walker could indicate "yes" and "no." He used a Bliss-symbol communication board at school, but interacted with his parents by using yes/no and eye gaze/facial expressions.

(6) Sensation: Sensation was normal.

(7) Education: Walker was in a non-graded, academic public school.

(8) Psychosocial Considerations: Walker was the youngest of several children. His parents felt that he was too immature to handle powered mobility. On the recommendation of their therapists, however, they were willing to try. Walker needed a lot of motivation to accomplish tasks because of the enormous amount of energy it required. His therapists felt that if he had a more energy-efficient means of mobility, he might become more active in other activities.

His parents had a van with a lift for family outings and the school had provided a van with a lift for transportation. The home was wheelchair accessible, and he lived in a neighborhood with paved roads and sidewalks.

His existing seating consisted of a CP Seat (Modular Plastic seating system - Pin Dot Products) in a manual wheelchair base.

Results

Walker was positioned in the powered mobility evaluation tool with bead modules. The joystick was positioned using the Magic Arm, just left of midline. He was taken outside the building into a parking lot for initial training. After explaining how the wheelchair operated, guiding his hand through the control motions, he was left to experiment with the movements himself. The therapist and his mother provided verbal feedback and directions. Periodically, the therapists took the control placement, and helped to guide his hands through the movements. Within an hour, Walker progressed from driving in circles, first to the left, then to the right, to driving forward and being able to drive all directions selectively. By the end of the evaluation (1 1/2 hours), he was able to follow his mother in a large circle around the parking lot to the street.

Recommendations

(A) Seating: The bead seating system was chosen as support because of its ability to provide aggressive contouring in independent seat and back components. This allowed Walker to be well supported for functional activities.

(B) Wheelchair Base: The Fortress Scientific 655 FS with standard proportional joystick control was chosen for a powered base, primarily because of parental choice. Any proportional drive chair could also have been used if the speed controls could be "tuned down" during the learning phase of operation. The Fortress acceleration rate was tuned down via the control box so that there was a slight delay in starting. This proved to be useful for indoor operation. Customized hardware allowed left of midline placement of the control box for optimal use by Walker. Once Walker was provided with the seating and powered mobility, it took him about two months to become a proficient user both indoors and outdoors. Walker soon enjoyed evening jogging sessions with his father, and was very pleased that he could move about independently. His parents related that he was more willing to initiate and work toward therapeutic and academic goals.

Conclusion

Technical options are now available to enable the severely physically disabled child to operate a powered mobility device (Trefler et al., 1986). Proportional and microswitch joysticks, single and multiple switch control systems, and joystick simulators now offer the clinician a variety of control options. Powered wheelchairs, carts and scooters can be purchased in a variety of sizes. The challenge for the clinical team today is to offer a thorough evaluation of a child's needs and abilities, and then to match the evaluation results with available technology. The selection of specific devices will depend on a child's age, physical abilities, positioning needs, available transportation, and home, school, and community environments.

When recommending technology for the child with a severe physical disability, one must remember that it is likely that the child will be operating more than one technical device with her limited motor skills. As well as evaluating an individual for a powered mobility device, we must keep in mind the child's possible need for an augmentative communication aid, computer control, or environmental control unit. Often, compromises in control placement made during the initial technology provision will allow the operation of all devices necessary.

A training period in the operation of the mobility device is required for most children. Some will require only a brief period of supervision which would include a discussion of safe driving habits, similar to that with a child receiving her first bicycle. Others, with more severe motor involvement, mental retardation, or perceptual limitations, will need more training in order to safely and accurately operate a powered mobility device. Consistent follow-up of the child's progress and changing technical needs will ensure that the provision of technology is successful.

Independence and responsibility must begin at a young age. Children in powered mobility devices can learn the safe operation of a device. They learn to avoid walls, to remember to ask someone to charge the batteries, and how to maneuver out of challenging corners. With the provision of a powered mobility device, they can explore, they can learn, and they can experience first-hand being children.

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Beneficial Designs, 5858 Empire Grade, Santa Cruz, CA 95060

Fortress Scientific, Ltd., 3750 Chestwood Drive, Downsview Ontario CANADA M35-2W6

Pin Dot Products, 2215 Belmont, Chicago, IL 60618

Prentke-Romich Company, 1022 Heyl Road, Wooster, OH 44691

CHOOSING A POWERED MOBILITY BASE
FOR PEDIATRIC CLIENTS

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Selection of a powered mobility base (PMB) for use by pediatric populations necessitates a careful match between the client and features of the base. As more options become available, the selection process becomes increasingly difficult. The final decision made by the prescribing clinician must be based upon the client's functional capabilities, operating environment, and available budget. It is necessary that there be a commitment between the client, family, school, physician, clinician, and durable medical equipment (DME) dealer in order to procure the most appropriate system.

This paper will discuss for the prescribing clinician the factors to consider when recommending features on a PMB. These factors are:

- Cost
- Maintenance/Serviceability
- Warranty
- Performance
- Dimensions
- Aesthetics
- Safety
- Adaptability/Adjustability
- Drive System
- Terrain
- Portability/Transportability
- Optional features available

Cost

The "true" cost of a mobility base is a combination of four factors: purchase price, maintenance cost, usable service life, and resale value. The retail cost of a powered base may not be an immediate concern to the clinician due to the availability of funds from a third party payer. This may be a danger, as it may prevent the clinician from studying lower cost alternatives. The "I want the best; spare no cost" attitude is a trap that can cause the purchase of an unusable base. Yet, the trap of focusing solely upon the base with the lowest retail cost may have similar results.

When comparing costs, it is important that the price of the unit include batteries and a charger. The features of the powered mobility base necessary to make a "complete" package (such as height-adjustable armrests) should also be detailed in the price. These items are optional on some bases and standard on others. The price on a unit may seem exceptionally good until the clinician finds out that the seat, footrests, armrests, and batteries are additional charges.

When purchasing the PMB, clinicians should be encouraged to compare costs among dealers and "bargain" on the price. Clinicians may observe a range of prices among DMEs. The amount of reimbursement varies with each paying source. If the third party payer is Medicaid or Medicare, there can be limits upon how much a dealer will be reimbursed. The reimbursement limit can be well below the suggested retail price. A DME may be reluctant to sell a higher priced mobility base due to the ceiling imposed by the funding agency. Therefore, informing the DME of the payer source may be helpful in negotiating a price.

The service life of a PMB depends upon how well the unit is constructed, how it is used, how well it is maintained, and how adaptable it is to needed changes. Chromed steel frames are less susceptible to rust than painted steel frames. A thin unsupported plastic shroud may be aesthetically pleasing but may not be as durable. If a PMB is well maintained by the user and family, its life will be significantly increased. The design of the base should allow for easy cleaning and access to the batteries. Surfaces that have texturing or areas difficult to reach will collect dirt and possible rust. Battery packs that are difficult to access should be avoided. One manufacturer's battery lid strap (E&J) is so difficult to release that it invites decreased care of the batteries. This strap should be changed before purchase. The use habits of the client will influence the life of a PMB. Areas of concern are terrain, distance travelled, and collision frequency. A mobility base that will be subject to rough terrain, curb jumping, and ten mile a day use will not last as long as one used exclusively in a school setting.

The annual maintenance cost of a PMB cannot be accurately predicted but the price of replacement parts can be a good indicator of projected maintenance costs. Batteries may account for more than half of the problems a user may experience (Bayer, 1981). The replacement cost of a battery depends on the type, size, and supplier. Gel cell batteries can cost almost twice as much as a wet cell. The amp hour capacity and usable life of a gel cell is also less. A DME will generally sell deep cycle lead acid batteries at a higher cost than a larger chain such as Sears.

A summary of battery and motor costs is included (see Appendix A). Also included in this summary is the cost of a replacement power module.

This list is intended to provide the prescribing clinician with an idea of what a potential service charge would be if the PMB's main electronic components are destroyed.

Maintenance/Serviceability

A powered mobility base will require daily attention and periodic maintenance. The batteries must be charged but not overcharged. During the selection process, attention should be given to the ease of charger hook up and operation. Lead acid batteries contain sulphuric acid, for which the cell levels must be "topped off" periodically. Access to the batteries should be easy enough to allow for quick visual inspection and water level maintenance. If it is difficult to see the proper water level, then overfilling and underfilling a battery is likely. The PMB should come with a hydrometer used for testing battery voltage. The mobility base should also be supplied with a detailed owner's manual that explains the care and maintenance of the unit.

One of the most important variables influencing the purchase of the PMB is the level of service that will be provided for the unit. If the PMB desired has never been sold in the area, or can only be serviced at the factory, then its purchase should be discouraged. If a DME does not have trained service personnel, the purchase should be avoided. To obtain an idea of what services that the DME provides, ask for a tour of the service area and request to see the replacement parts stock. A DME who does not carry replacement parts for the stock sold cannot perform an appropriate level of service. Without proper stock and trained service personnel, a DME may be tempted to replace a complete power module rather than replace a circuit board. The difference may be $1,200 versus $200.

"Downtime" due to servicing can cause extra expense in equipment rental, travel, and missed work. The added "expense" of psychological stress due to the loss of independence must be considered. The distance to a service center can be a determining factor in the base recommended for purchase. A simpler base may allow a member of the user's family or a friend to locate a problem such as a micro-switch. Yet if the problem is more complex, such as an inductive joystick, it is unlikely that the service could be completed without trained personnel.

Warranty

The details of the PMB warranty should be explained prior to purchase. It is common for mechanical systems to carry a one-year warranty but electronic parts are seldom warranted past 90 days. The warranty on the batteries should also be explained.

Performance

Speed: The top speed of a PMB may be exaggerated by the dealer. The age and ability of the client will determine what speed is desirable. Most models have variable speeds up to 4.5 miles per hour. Top speed is not as important as the ability for the clinician to set the maximum speed in a manner that cannot be altered by the client. Performance-plus packages (Invacare Arrow, 7 mph) and high-speed gearing (Sherry Sparky, 9 mph) should only be considered for older teens and adults.

Related to speed is the unit's acceleration rate. This rate refers to the time a PMB takes to go from stop to full speed. The faster the acceleration rate, the jerkier the movement of the mobility base will be. Too slow an acceleration rate will create unresponsive control. Some units can be adjusted. PMBs that have a proportional speed controller offer more control to the user. The further a proportional controller is moved, the faster the unit travels. A micro-switch controller requires that speed levels be mechanically switched. Acceleration and speed changes can be abrupt. Although the client has less fine control with a micro-switch system, the need for serviceability and cost of the unit may be significantly less.

Torque: The available torque of a PMB can determine the type of terrain a unit can handle. A higher torque motor will allow a mobility base to overcome obstacles and ascend ramps. Many manufacturers are reluctant to advertise what degree of slope a PMB can handle, due to the unknown variables of user weight and surface condition. Some mobility bases are advertised as being able to jump a 3" curb (Fortress 655). A prescribed base should be able to traverse a minimum 10% gradient, which is equivalent to a 1:10 ramp. One wheelchair, the ELK1024, can have three different torque limits set. This can be important when training a client, because even a slight collision will cause the unit to stop.

Range: Range is how far a unit can travel upon level ground on a single charge. This is relative to the capacity of the power source and the efficiency of the motors. Client weight, battery condition, and the type of terrain will also affect the maximum distance a unit can travel. A child may have sufficient range during the school year, but exhaust the power supply prematurely in the summer. A 12-18 mile range should be adequate for most users.

Ground Clearance: If outdoor use is anticipated, then ground clearance can be an important feature. Obstacles such as curbs, rocks, sticks, and thresholds can cause problems if the ground clearance is insufficient. Clearance is especially important in snow.

Turning Radius: The user's environment will dictate how much area is needed to turn completely around. Bases with three wheels will generally have a longer turning radius because the front wheel is positioned forward of the user's feet. The summary (Appendix A) or owner's manual may provide valuable information.

Non-Powered Propulsion: There will be many instances when a PMB will have to be pushed manually. It is difficult for an attendant to guide a power chain using the controller from a standing position. Therefore, a mobility base should have the ability to disengage the motor from the drive wheel. The force necessary to push a PMB should not be excessive. The method of disconnecting the motors should not require the attendant to bend over and reach underneath the base because, if the unit is accidentally activated, the attendant can be injured.

Dimensions: A PMB should be as narrow as possible to reduce access problems. The overall length, including footrests, will dictate the amount of room needed to maneuver the base. The length from wheel to wheel will also be an important consideration for use on van lifts. Some three-wheeled bases can not be used on "swing-type" lifts, unless a special platform is installed to compensate for the extra length. The overall width of a mobility base can be more than the manufacturer specifies because of the extra width added by the joystick controller.

Ride: Shock absorbing characteristics can be built into a mobility base's frame and wheel housings. The use of pneumatic tires will provide a smoother ride but require more maintenance. Some PMB frames have a pivoting front which compensates for uneven terrain and provides better climbing ability (Fortress 655, 755, E&J Explorer, Invacare Arrow XT, and Elki 024).

Aesthetics

The aesthetics of the PMB play a major role in the selection process. Manufacturers are adding "sport type" styling to attract users. Ultimately there must be a balance between "good looks" and performance. Proportion, form, line, color, symmetry, sound, and touch should all be considered when evaluating aesthetics.

Proportion refers to the relationship between the user and the base. The client should not be dwarfed by the size of the base. Consideration must be given to the eye level of his peers. While being at eye level is important, care should be taken not to create a bulky or unstable package.

The form or design of a PMB should promote the person, not the machine. The machine should not be the prominent focus. A base that looks like something out of the Flintstones or Jetsons will detract from the user's image. The base should blend with the environment and be more like a mini-bike than a wheelchair.

Color can be an important decision for a child as it can reflect a portion of his personality. Chrome can be institutional in appearance but is very durable. Black is always a safe choice.

The lines of a PMB should lead one's attention to the user. Lines should be soft and not harsh, and this will make for safer, well rounded edges.

The symmetry of a PMB will depend upon its drive train and features. In general, the look of a balanced device is desired.

Background noise generated by motor whines (E&J Pacer), electro-mechanical brake click, gear grind or frame creak may detract from the desirability of a PMB. Excessive noise may make it difficult to blend into the environment. There has been a considerable effort of most manufacturers to decrease system noise.

The PMB should feel warm and smooth to the touch. Contact areas should not hold the cold, and good air circulation should be provided.

Safety

One of the most important features of a PMB is access to the brakes. There are several brake types and these can be described as mechanical, dynamic, regenerative, or electro-mechanical. A mechanical brake is usually a lever that can be locked into position against the wheel. This is the simplest of systems and may be the only type on a less expensive PMB. Mechanical brakes have a tendency to slip and must be kept in adjustment. The presence of water on the surface of the tires or the inflation pressure can affect this braking system. Mechanical brakes cannot be used to slow down a moving PMB.

Dynamic braking refers to the ability of a mobility base to gradually come to a stop. In some models, the amount of time the mobility base uses to come to a full stop can be adjusted. This time period is called the deceleration rate. Dynamic braking is particularly important when descending a slope because the PMB is prevented from picking up excess speed. A mobility base that does not have dynamic brakes will "freewheel" or coast to a stop. This is considered an uncontrolled stop and can lead to collisions.

Regenerative braking is the least important braking feature. It allows the mobility base to recharge the batteries while descending slopes. The overall effect would be minimal on most terrain.

Electro-mechanical brakes can be an important option and are offered as a feature on several PMBs. These brakes automatically lock the mobility base's motors and prevent rotation of the wheels. Clients who cannot apply mechanical brakes should have electro-mechanical brakes.

Setting limits on speed and distancing user access to this control will prevent the user from exceeding safe limits. The remote site may also have to be inaccessible to the user's peers.

The location and style of the on/off switch should be considered. The client should have access to this switch, yet the potential for accidental activation should be evaluated.

The battery charger should have a "lockout" feature that prevents movement of the PMB while the charger is plugged in. The user should be educated in the charging technique, the dangers of handling sulphuric acid, and the importance of charging in a well-ventilated area.

The prevalence of castor shimmy in a PMB can be dangerous. The rapid oscillation of a front castor wheel can cause frame breakage and reduced control. Corrective action can be taken to decrease this phenomenon (Kauzlarich, 1984). A base that exhibits this behavior and cannot be adjusted should be avoided.

If a mobility base allows a client to traverse rough terrain, then the design should offer a low center of gravity. The potential for tipping a base over can also occur indoors. Some manufacturers will post warnings about excessive speed in sharp turns, and bases of this nature should be considered with caution.

Other safety features that should be considered with a mobility base include seat belt, rear anti-tips, light reflective surfaces, and battery level indicators.

Adaptability/Adjustability

The ease by which a PMB can be changed to match a user's needs depends on the electronic and mechanical features supplied by the manufacturer. The options previously described include acceleration rates, deceleration rates, speed, and torque limiting. Another important option is input dampening. This feature filters unwanted input caused by the client's spasticity or tremors. Input dampening should be adjustable to match client needs.

Operation of the mobility base can be influenced by the physical size, placement, and shape of the controller. Some joysticks come packaged within a larger control box that contains all of the circuitry of the base. This larger box can make midline positioning difficult (Abec Fireball 40, Invacare Ranger II, Rabbit). Some joysticks are oversized because of extra features housed within the control (Invacare Arrow).

The type of tiller used on a three-wheeled base can be a limiting factor if the tiller cannot adjust to match the user's reach. A majority of PMBs will be adapted with customized seating, and therefore the frame style should not inhibit these changes. Some bases such as the Orthokinetics Pony can be purchased with adaptive seating components. The pedestal-mount bases (Fortress 655/755, E&J Explorer, Invacare XT, Elki 024, and most three-wheeled bases) provide freedom to construct adaptive seating. Fortress advertises bases with a large variety of seating systems, such as Otto Back and Contour U.

A base should have the ability to grow with the client. Features such as height-adjustable armrests and adjustable footrests are desirable. Adjustment of the seat depth, seat width, and back height should be as simple as possible. Bases with folding frames will require that crossframes be replaced in order to allow for client growth.

The input signal a client must use (i.e., short throw joystick, sip and puff, body switches, touch plate) is important to consider when selecting a base. The possibility that a client's function may decrease or increase must be evaluated in order to choose a base that will allow for variable input methods.

A short throw joystick allows control for a user who has a minimum range of motion or who may use the system with the chin. The sip and puff controller requires that the user sip and puff small amounts of air with differing degrees of pressure. Body switches that control the four directions of the base can be placed in the most appropriate location.

Drive Systems

The drive system of a PMB can be divided into the following categories: power source, input device, control module, and motors. Simply put, the input device generates a signal that the control module decodes, which then directs the amount of power to be delivered to each motor.

The power source (batteries) can be gel cells, sealed lead acid or unsealed lead acid batteries. These batteries should always be of the deep cycle variety. The size of the battery pack is stated in group size (i.e., 22, 24, 27). Available power increases with the size of the battery. The amount of power a battery is capable of holding is expressed in amp-hours. A gel cell battery can be a safer alternative but it will be more expensive and has less amp-hour capacity. Sealed deep cycle lead acid batteries are becoming available. These batteries require less maintenance than the unsealed variety. The YUASA NP brand appears to have a good record.

Unsealed lead acid batteries can have serious drawbacks due to the possibility of acid spillage, but they are relatively inexpensive, easy to obtain, and can have the best performance characteristics if properly maintained. Only gel cells can be taken aboard an aircraft without custom packaging.

Input systems have been discussed earlier in this paper and have been separated into micro switch and proportional devices. Most three-wheeled bases control forward and reverse travel via the input signal and the steering is performed mechanically. The force to operate a joystick varies from base to base. Extensions can be placed on the joystick to compensate for strength or grasp. For clients who have poor control and good strength, a more durable joystick may be needed. Invacare offers a heavy duty style joystick as an extra feature with the "switch options package".

Control modules can allow the clinician to shape the client's input signal and compensate for functional limitations. Generally, the more shaping potential a system has, the more expensive the base will be. Control modules can be the most expensive replacement item on a mobility base. The design of this module should allow for subcomponent replacement. Most manufacturers will also sell rebuilt units. The highest price control module is for the Invacare Turbo (2750). The control module should be mounted in a secure manner and in a position that will not be subject to impact. Power and motor connectors should be clearly labeled and secure enough to prevent accidental unplugging.

Motors that propel a PMB can do so in several ways. These methods include direct, belt, chain, and friction drive. A direct drive motor does not allow slippage between the drive components because the motor is connected directly to the wheel. On most models, gear reduction is utilized. Some models tend to create more noise (Meyra). Belt drive is one of the most popular methods of transmitting motor power to the wheels. This method requires that the belts be changed periodically and adjusted to compensate for stretch. Water on the belt's surface can cause excessive slippage. Slippage cannot be avoided in a belt drive system unless the belt is cogged and engages into a cogged pulley. The use of a belt drive system allows the motors to be placed away from the wheels. This remote placement can provide better access for servicing and clutch placement.

Chain drive is used on some three-wheeled bases. The chains prevent slippage but can be noisy. Friction drive is used primarily for add-on power units. The motors turn a roller that presses against the mobility base wheels. This type of system is not suited for long term outdoor use.

Battery chargers are an important link in the overall efficiency of a drive system. The supplied charger must be compatible with the type of batteries used in the system. Some chargers are not recommended for gel cell applications. If a client wishes to change battery styles, then chargers may have to be changed. Tests have also shown that some chargers are affected by decreased supply voltage (Kauzlarich, 1984). The results will be that the batteries may need a much longer time to become fully charged.

Terrain

The areas where a PMB will be used can have an impact on which base is purchased. Some bases are designed specifically for smooth indoor surfaces and even a deep shag carpet may cause them to stall. Bases with smooth tread drive wheels are made for indoor applications and level outdoor terrain. If the prime use for a mobility base is the outdoors, then expecting it to perform well indoors can be frustrating. Outdoor machines will bring in snow and dirt between the tread on the tires. These machines can also cause damage to the interior of the house. Care should be taken to protect walls and door jambs. An indoor model may scratch a wall upon impact, while an outdoor model will punch a hole in it.

Portability/Transportability

The prescribing clinician should be aware of the transportation which will be available to the client. If the client's family does not own a van with a lift and tiedowns, will they be willing to purchase one? What kind of public transportation is available in the area? Does the school bus have a lift? Will the tiedown systems be compatible with the base chosen? Asking these questions will prevent the purchase of a base that is environmentally incompatible.

If there is no transportation available, then consideration should be given to models that disassemble and/or fold into easy-to-handle packages. The size and weight of the largest piece should be easily lifted into a trunk. The ease of disassembly and the number of pieces must be considered. The clinician should plan on the system being assembled during inclement weather and in the dark. Provisions for stowing a disassembled PMB in the passenger area of a car must be considered. Proper stowage of the base should prevent parts and lead acid batteries from becoming projectiles in a crash.

If a family does not have a van with a lift, then an alternative may be to use a trunk or hatch lift. A full sized three-wheeler can be stowed within the back hatch or trunk of some vehicles by removing only the seat of the PMB.

Optional Features

Manufacturers of PMBs can offer a wide variety of optional features. Some bases may appear very similar, yet available options for one variety may create a more individualized package. Consider the need for the following features:

- Back recline: powered and manual
- Angle in space adjustment: powered and manual
- Seat height adjustments: powered and manual
- Extended range packages
- Battery level indicators
- Seat swivel
- Quick change wheels
- Extendable wheel base

A summary of features is provided to give the clinician a general overview of current commercially available options (Appendix A). This may provide an initial screening of devices considered appropriate for a client. Test drives and hands-on experience will be needed to make informed decisions. Some features such as "degree of grade capable of climbing" are not consistently published by manufacturers. This is due to the variables that may affect PMB traction and load carrying capability. The suggested retail cost of the bases may or may not include batteries. The components listed for comparison (batteries, motor, and control module) are suggested list prices and do not take into account the possibility of purchasing a rebuilt component or credits for a trade in. Some of the bases were new at the time of this survey and price lists were unavailable. All information was provided by manufacturer representatives or literature.

Not every PMB available in the U.S. is listed. This summary is meant to provide a cross-section of manufacturers and bases. Research by the clinician to locate local or regional manufacturers is encouraged.

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Kauzlarich JJ. Electric wheelchair battery charger performance. In Proceedings of 2nd International Conference on Rehab Engineering. 1984:226-229.

APPENDIX A

Man/Dist	Model	Type of Unit	Battery Cost (apiece) $	Battery Type (volt)	Weight WB	Weight WOB	Turn	Width in.	Length in.	Speed (MPH)	Range	Grade	Motor Cost $	Control Module Cost $	Sugg. Retail Cost $
ABEC	40	4W PJ	50	LA(2) 12	105	57	N/A	24½	40	4.5	12-20	7°	440	1295 w/PJ	3595 w/bat
	Fireball	4W MJ	50	LA(2) 12	86	46	N/A	21	32½	2.5	12-20	7°	310	565 w/MJ	2335 w/bat
	Fireball 40	4W PJ	50	LA(2) 12	94	56	N/A	21	21½	4.5	12-20	7°	440	1295 w/PJ	3595 w/bat
AMIGO	Mini	3W MT	85	GC(1) 12	95	73	36	24	42	4	8-10	10%	385		1795-2095
	Ulta 110	3W PJ	173	GC(1) 12	109	84	32	21-3/4	36	3	9	10%	105	1100	3295
	Ulta 220	4W PJ	173	GC(1) 12	112	87	32	21-3/4	36	3	9	10%	105	1100	3595
BRAUN	T 1100	3W PT	130	GC(2) 12	203	100	30	25	38	4.5	15	N/A	83	525	2750 w/bat
	J 1100	3W PJ	130	GC(2) 12	203	100	30	25	38	4.5	15	N/A	83	990	3330 w/bat
DAMACO Add on	D 88	PJ	100	GC or SLA (2) 12	67	31				5.25	20	9°	108	810	2145 w/o bat
EVEREST & JENNINGS	Mobie	3W PT	96	GC(1) 12	131	79	36	22 - 26	36 - 38	4.5	20	7°	82	470	1,695-1,995
	Pacer	3W PT	60	LA(2) 12	176	124	N/A	25	47	5.0	16	7°	N/A	N/A	2,295

Man/Dist = Manufacturer or Distributor

Type of Unit:
4W = 4 wheels
3W = 3 wheels
PJ = proportional joystick
PT = proportional tiller
MJ = microswitch joystick
MT = microswitch tiller

Battery Type:
GC = gel cell
LA = lead acid
SLA = sealed lead acid

Weight:
WB = with battery
WOB = without battery

TURN = Turning Radius

Man/Dist	Model	Type of Unit	Battery Cost (apiece) $	Battery Type (volt)	Weight		Turn	Width in.	Length in.	Speed (MPH)	Range	Grade	Motor Cost $	Control Module Cost $	Sugg. Retail Cost $
					WB	WOB									
EVEREST & JENNINGS	Explorer	4W PJ	60	LA(2) 12	215	127	N/A	25	35½	5.8	25	9°	684	1125	4,965 w/o bat
	Marathon	4W PJ	60	LA(2) 12			N/A	24 - 26	32½	5.1	20	9°	507	1120	4,895 w/o bat
FORTRESS SCIENTIFIC	2000 FS	3W PT	86	LA(2) 12	177	107	40	24	42"	5	20	N/A	675	900	2,260
	655 FS	4W PJ	89	LA(2) 12	213-243	137-167	30	24	29¼	5.7	20-30	12°	675	1300	4,424 no seat
	755 FS	4W PJ	89	LA(2) 12	152	100	28	24	26½	5.7	10-20	12°	675	1300	4,424 no seat
INTERNATIONAL MEDICAL E & J CANADA	Scout MPV	3W- MJ	60	LA(1) 12	69	47	31	20½	37	3.5	N/A	N/A	426 CAN.	463 CAN.	2,445 U.S.
INVACARE	Rabbit	4W PJ	60	LA(2) 12	133	93	N/A	23-25	28½	4	N/A	9°	766	1,178	3,056
	Jaguar	4W PJ	60	LA(2) 12	133	93	N/A	23-25	28	5	N/A	9°	722	1,259	4,126
	Turbo	4W PJ	N/A	SLA(2) 24	190	150	N/A	23 5/8	31½	4	N/A	N/A	631	2,750	6,850
	Compact Ranger	4W PJ	N/A	SLA(2) 12	118	68	N/A	25	43	3.4	N/A	9°	866	1,892	3,140
	Ranger X	4W PJ	60	LA(2) 12	180	104	N/A	22-26	33	5	N/A	9°	574	1,259	4,123

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					WB	WOB									
INVACARE	Arrow	4W PJ	60	LA(2) 12	190	114	N/A	22-26	33	5	N/A	9°	1037	1,649	4,863
	Dart	3W PJ	60	LA(2) 12	125	85	N/A	23½	39½	5	N/A	9°	N/A	N/A	2,000
	Arrow XT	4W PJ	90	LA(2) 12	235	135	N/A	25	45	5.5	N/A	9°	N/A	N/A	4,800
MED NET HUKARE	Elki 024	4W PJ	60	LA(2) 12	205	125	36	23½	35	5	20-25	12°	135	180	4,255 w/o bat
ORTHOKINETICS	Sierra Front Wheel Drive	3W PT	95	GC(2) 12	132	92	32½	21½	42	4.9	27	10°	80	250	2,150 w/bat
	Sierra Rear Wheel Drive	3W PT	95	GC(2) 24	153	113	35½	24 3/4	46½	5.3	25	12°	300	250	2,600 w/bat
	Pony 4312	3W PT	95	GC(1) 12	79	59	24	18	31	4.2	8	10°	80	200	1,750 w/bat
	Pony 4313	3W PT	95	GC(1) 12	85	65	24	18	34½	4.2	8	10°	80	200	1,815 w/bat
	Bravo	3W PT	95	GC(1) 12	80	60	32½	18	40	4.0	10	7°	80	325	1,495 w/bat
SAFETY REHAB SYSTEMS	909ZX	4W PJ	95	GC(2) 12	102	53	N/A	22½	27½	2.5	N/A	N/A			2,900 w/bat
SHERRY PRODUCTS	Sparky	4W PT	60	LA(2) 12	185	133	31	21½	36	5-9	20	N/A	200	475	2,650
		4W PJ	60	LA(2) 12	185	133	31	21½	36	5-9	20	N/A	200	695	
SOLO															
VOYAGER	Unitrol	3W MJ	112	GC(2) 12	155	85	31	22	41	6.5	30	20%	132	325	2,366

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TURN = Turning Radius

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Torrance, CA 90501
213/533-0306

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7500 Bluewater NW
Albuqueque, NM 87105
800/248-9130

Braun
1014 S. Monticello, P.O. Box 310
Winamac, IN 46996
219/946-6157

Damaco
96212 Lurline Avenue, Unit A
Chatsworth, CA 91311

Everest & Jennings
3233 East Mission Oaks Boulevard
Camarillo, CA 93010
805/987-6911

Fortress Scientific
61 Miami Street
Buffalo, NY 14204
800/387-3611

International Medical
14322 Bonelli Street
City of Industry, CA 91746
818/369-7002

Invacare
899 Cleveland Street, P.O. Box 4028
Elyria, OH 44306-2125
1-800-INVACARE

Med Net Hukare
4950 West Dickman Road, P.O. Box 1438
Battle Creek, MI 49016
616/962-3800

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P.O. Box 436
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